IDA DOCUMENT D-1519
(Revised)

# EXECUTIVE REPORT
# SPACE SYSTEMS TECHNOLOGY WORKING GROUP

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September 1994





*Prepared for*
Office of the Principal Deputy Assistant Secretary of Defense
(Dual-Use Technology Policy and International Programs)





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Contract DASW01 94 C 0054
Task T-C2-1236.1

# PREFACE

This publication documents work done for the Principal Deputy Assistant Secretary of Defense for Dual-Use Technology Policy and International Programs. In addition to providing a basis for policy and priority decisions regarding technology support, cooperative agreements and export controls, the results of this analysis will be incorporated into the Militarily Critical Technologies List (MCTL) and Foreign Technology Assessments (FTAs).

# FOREWORD

In October 1992, the Director of Multinational Programs, Undersecretary of Defense for Acquisition and Technology, tasked the Institute for Defense Analyses (IDA) to assess space technologies. The objective of this assessment was to identify those technologies that are space unique, militarily critical, and dual-use to provide the basis for policy and priority decisions regarding technology support, cooperative agreements, and export controls. To accomplish these tasks, IDA organized a Space Systems Technology Working Group (SSTWG) with Dr. Raymond V. Wick, Chief Scientist for the Space and Missiles Technology Directorate of the Air Force Phillips Laboratory, and Major General Gerry Hendricks (USAF, Retired) from IDA as co-chairpersons. Twelve subgroups of government, industry, and academia representatives were formed to address the major space system technology areas. The Principal Deputy Assistant Secretary of Defense (Dual-Use Technology Policy and International Programs) was the DoD sponsor for this SSTWG effort.

Each of the space technology subgroups was asked to identify and describe the militarily critical space technologies (using Service mission deficiencies as a major input), explain their military significance, identify the key quantitative parameters involved, estimate their dual-use potential, assess their foreign availability, and recommend appropriate actions. For critical military parameters, the objective was to define more completely the threshold specifications in order to free from control those technologies that were not militarily critical. Also, because of the importance of the economic and the military and scientific aspects of space technology, the SSTWG subgroups were asked to discuss the economic security implications of the critical military and dual-use technologies. The results of these individual subgroup efforts and the subpanel membership lists are published in the "Technical Report," IDA Document D-1521. In addition, the "Scripted Briefing," IDA Document D-1520, can be used as a supplement to this document.

This Executive Report summarizes the findings and conclusions of the subgroups. It contains a Summary with conclusions and recommendations of the SSTWG, an Introduction (Section I), and a discussion of each space technology area (Section II).

Section III has three sets of tables. The first set (Table III-1) summarizes all identified critical and unique space technologies. The second set (Tables III-2 through III-13) lists the critical technologies and their critical parameters in each of the 12 functional areas. The third set (Tables III-14 through III-23) lists 10 of the 12 technologies and includes the values of parameters that have been achieved in laboratory and the corresponding production capabilities to date for each technology.

The conclusions and recommendations of this SSTWG study verify several of the recommendations by the Vice President's Space Policy Advisory Board, particularly those recommending strong support of space research and development (R&D), the improvement of the U.S. launch capability, and the removal of impediments to the economic growth of U.S. space activity.

This report supports Secretary Widnall's assertion that: **"Space systems signal America's stature as a world power and aerospace nation. Control of space and access to it are fundamental to economic and military security. Ask the 20 foreign countries who will have space capabilities by the year 2000: a presence in space implies influence, power and security"** (Sheila E Widnall, Secretary of the Air Force, September 1993).

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# SUMMARY

## A. BACKGROUND

The Space Systems Technology Working Group (SSTWG) study was formed as a result of two major concerns. The first was an industry concern about the export restrictions on militarily critical technologies, with the resulting negative effect on global space commercial business opportunities. The second was a recognition within the Department of Defense (DoD) and industry that the primary planning documents used to prioritize spending and to restrict foreign trade treated space technology in a cursory fashion rather than as a focused priority technology area. This study complements recent Joint Directors of Laboratory technology studies, directed towards fostering attention on critical military and military space technologies.

Examples of this casual treatment of space technology include the Militarily Critical Technology List (MCTL) space technology coverage, which gives fractional and varying levels of technical detail to space technology items scattered throughout the 15 established technology sections, and the DoD Key Technology Plan, in which space-unique technologies are scattered throughout the 11 recognized categories but space technology is not recognized as a distinct entity or category. This format makes it difficult to locate specific space technology items and to identify the unique performance parameters that determine if they are truly **critical space technologies that should be given priority support.** As a result, numerous space-related technologies are not addressed in the key DoD plans.

The United States has recognized the importance of space and space technology to its national and economic security since the beginning of the space era. Consequently, we have played a dominant world role in developing and using space technology. The importance of our **military and commercial space assets and their capabilities**, in peacetime and in combat, was demonstrated vividly during the buildup and conduct of the Gulf War. With the decline in available defense resources, the United States has an added impetus to identify **critical military space technologies**. Fully supporting all aspects of

**national planning for the development of these technologies will contribute significantly to our continued military and commercial leadership in space.**

U.S. space leadership in the 1960s, 1970s, and 1980s enhanced our economic strength and strengthened our technological and military capabilities. Recent global changes, including the fall of the Soviet Union and the emergence of new economic centers and alliances, place greater pressure on U.S. space leadership. More countries are competing for space leadership, and they are acquiring the needed technologies. If the United States does not aggressively pursue the goal of remaining the dominant space power, **other countries will seize the opportunity**. France is becoming the leader in low-cost, highly reliable commercial launchers, and Russia and China are working diligently to establish a commercial space industry. An awareness of these challenges within the Congress and recognition by other national leaders is crucial to build the foundation for the resource support necessary for continued U.S. leadership in space.

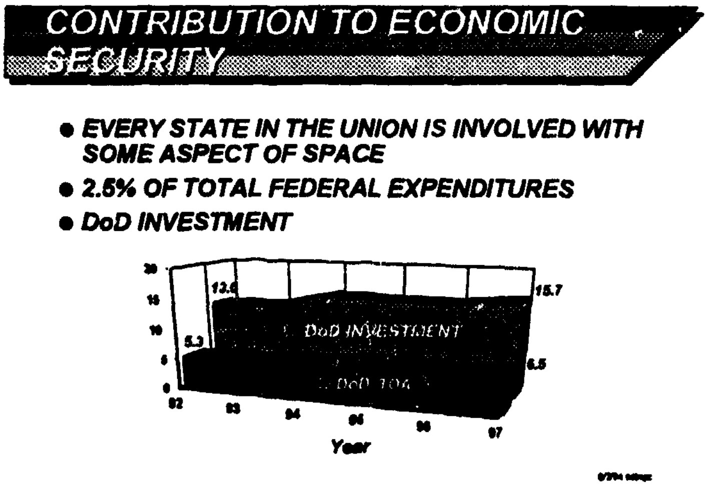
If the United States is to maintain its military space leadership role, the DoD must ensure that military space science and technology requirements are adequately **identified** and specifically defined and **documented so that critical space development programs** receive the required resource support.

## B. ECONOMIC IMPACT

Although the **military threat** to national survival—a characteristic of the bipolar Cold War years—is **greatly reduced**, the military **threat of regional conflict is, and will remain, high**. A more important and immediate menace to the United States **is the economic threat posed to the present U.S. aerospace industry.** The **U.S. share** of the global aerospace market **has dwindled significantly** in recent years. This market shrinkage has had a direct impact on the U.S. space industry as a whole, a fact emphasized in the recently completed *Space Industry Study* chaired by the Vice President of the United States.

In addition, the **European and Pacific Rim** countries are mounting **state-sponsored efforts** to become **leaders** in the **global aerospace market, particularly where there appears to be a commercial payoff (i.e., space communications and launch services).** Substantial investments have been made to support research, development, test, and evaluation (RDT&E) facilities and to educate scientists and engineers. **Business leverage alliances** and **partnerships** are growing between governments, industry, and their educational institutions. **If this trend continues, the**

**United States could be relegated to second place** (or worse) in many categories of the world aerospace market early in the 21st century.




The space contribution to our national economy is considerable. Every state in the union has research, development, or manufacturing activities related to current and projected space efforts. Space expenditures currently amount to more than 2.5 percent of the Federal Budget (about $35 billion) and represent 15 percent of the DoD investment account through 1997. The $5 billion commercial space export business in 1991 was the equivalent of exporting about 500,000 automobiles. This export business could increase significantly if the United States maintains its competitive edge in the development of new cost reducing technologies with advanced systems capabilities.

The question is as follows: How can the United States best exploit its space technologies and maximize the contribution of these technologies to military and economic security? The United States' long-term investment in the military capability necessary to defend the itself must be protected. Pressures from U.S. industry for expansion into commercial space markets around the world will continue, and limiting the access of space technologies to these foreign markets must be weighed carefully. Today, U.S. space industry access to the global market is often being restrained through limitations on the **foreign sale of dual-use technologies.** For the space-critical technologies at risk, the challenge for the U.S. government is to **achieve a reasonable and prudent balance between national security requirements, military interests, and economic interests.** To be successful, government and industry must communicate and coordinate.

One approach to managing dual-use technologies is to emphasize **selling products or allowing the use of the technology products rather than selling the development and production technologies themselves.** A good example of this approach is land satellite (LANDSAT) imaging. Images, not the optical systems that produce these

images, are sold commercially. Another approach is to develop more cooperative research agreements between government and industry to pursue reduced-cost launcher and payload technologies and more international cooperative agreements with other friendly countries.

## C. DISCUSSION

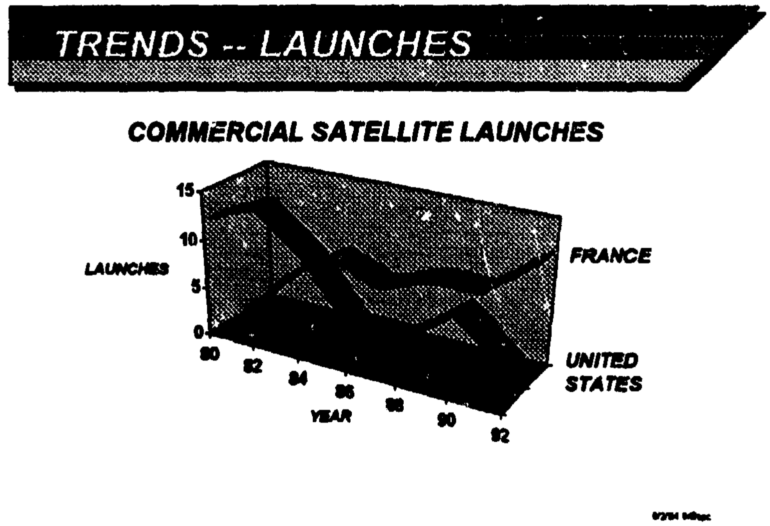
The ability to manage space technologies and capabilities is critical to overall U.S. space leadership, especially in the management of dual-use space technologies. Greater use, both commercially and militarily, will lower the unit cost to all users. For the militarily critical space technologies, their security value versus commercial access to them and the resultant effect on our global competitive position will require continual evaluation. A continuing dialog about U.S. long-term objectives is required to provide the basis for identifying and restricting those few militarily critical space technologies that should not be exported because of national security reasons. With the emphasis on broadening the global commercial opportunities for all technologies, including space, DoD will need sound and very specific rationales for the technologies judged to be militarily critical.

As the United States transitions from policies that governed past export controls, it must recognize the need for changes and make the needed adjustments. Today, **some noncritical technologies**, such as **all** "space-qualified" cryocoolers, **are controlled. Under the new export control regime, noncritical technologies must be reevaluated to determine whether controls are necessary**. The past definitions were too general and covered categories of technologies rather than specific technology elements, items, or systems. However, we have identified **three technologies that are not controlled but are *critical* and should be controlled.** When such technologies are identified, the United States must effect prompt changes in export controls. In the first case, the penalty for not acting is the **loss of commercial sales** and their attending economic impacts. In the second case, the potential **loss of a militarily critical technology** that adversely affects U.S. national security is a real possibility.

The ability to properly define critical technologies, to adequately assess their priority in relation to U.S. security requirements, and to effectively communicate this information to DoD and Congressional leadership provides the best assurance that funding for these critical space technologies will be forthcoming. **Without adequate visibility**

**and understanding of space technologies' military and economic contributions, the needed support to bring these technologies to full maturity will erode.**

## D. TRENDS




A relatively flat trend in U. S. defense space budgets is forecast over the next few years. In total, the U.S. **commercial space market is expected to continue to grow, albeit slowly.** The greatest growth areas are expected to be communications and ground surveillance systems. Forty new communication satellites are scheduled for launch in the next 5 years. These launches are projected to result in a nominal 4 percent growth per year in new space-based C/Ku-band transponders.

On the negative side, **U.S. commercial launch capability is not as cost effective as that of our foreign competition. As a result, we are now launching fewer commercial satellites than the French.** In the 1991–1992 period, France launched 12 satellites, and the United States launched 4 satellites. **This situation, if unchanged, will have serious long-term implications for the U.S. space program.**

The public space euphoria of the early 1980s, with talk of long duration space missions and future colonization, has subsided. Recent congressional actions suggest that space, as a priority, has taken a back seat to the demands for budget balancing and increased funding for social concerns. **Highlighting and emphasizing to the public and Congress the value and importance of today's space technologies should have a positive direct effect and provide the best opportunity to maintain U.S. space dominance.**

## E. TECHNOLOGY INVESTMENT

Technology investment has the potential payoff of maintaining U.S. technological performance leadership and a leveraged position in the world economic arena. Countries and companies that have large research and development (R&D) investments appear to do well. With new technologies, the challenge is obtaining the needed investment up-front to realize the desired long-term benefits.

The French Ariane is an example of a technology investment strategy that has paid dividends. By investing in launch operations with modernized and automated checkout and launch, Ariane can launch a *comparable* Atlas Centaur or heavy-lift Titan IV with a 100-person ground crew in about 10 days. In comparison, the United States needs 300 people and 55 days to launch an Atlas Centaur and 1,000 people and 90 days to launch a heavy-lift Titan IV. Through this quick, low-cost launch service, the French are capturing most of the world's commercial satellite launch business.

**The United States has the enabling technologies to lead in low-cost launch systems.** However, we lack **national priority, investment strategy, and resource support to systematically develop these technologies for the next-generation propulsion systems and launch vehicles.**

Given this, the crucial questions are as follows: How can the United States best exploit space technologies and maximize the contributions of these technologies toward our military and economic security goals and objectives? How can the United States provide cost-effective technological advances to overcome other countries' leads in specific areas of space capabilities?

During this study, the technology subgroups made judgments about the adequacy of current critical technology support. These judgments, though outside the charter and objective of the SSTWG, were included because of their potential utility for the offices and agencies responsible for developing these technologies.

## F. RESULTS

This study identified and described the key quantitative parameters of militarily critical space technologies and categorized the dual-use potential and military significance of these technologies to provide a basis for policy and support priority decisions.

Of primary concern to DoD is the overall category of technologies that are "militarily critical." These technologies are defined as those that are essential to

accomplishing a military mission or objective—especially in overcoming a military mission area deficiency—or are new enabling technologies that have potential for significant increase in a military capability. They represent the key to maintaining military space capability leadership.

"Space-unique" technologies are those that support only the space mission. This important category of military critical technologies is identified in this study but, at this time, is not specifically recognized in key DoD documents. These technologies are not automatically being nurtured by other nonspace mission thrusts. Visibility to senior DoD and Congressional officials is key to future development of these technologies.

Also identified are "dual-use" militarily critical technologies that have the potential for military and commercial applications, with payoff for both. By being more precise and improving the definitization of parameters that describe these dual-use technologies, the United States can release formerly controlled technology for commercial export to strengthen its space industry and, at the same time, protect those technologies that support security requirements.

Having categorized these technologies, part of the study charter was to examine the implications of export control and "dual-use." Some commercial dual-use technologies do not contribute to militarily significant technology since their operating parameters or functions are significantly different. A case in point is the electronic components of some military communication satellites that must operate in a more hazardous radiation environment than the equivalent commercial satellites.

Since visibility and support are fundamental to furthering the R&D of these space-unique militarily critical technologies, the SSTWG investigated the prospect of entering into partnerships through Cooperative Research and Development Agreements (CRDAs) with industry and Memorandums of Understanding (MOUs) with specific allied nations to more effectively develop the technologies. Section III lists specific recommendations for each technology.

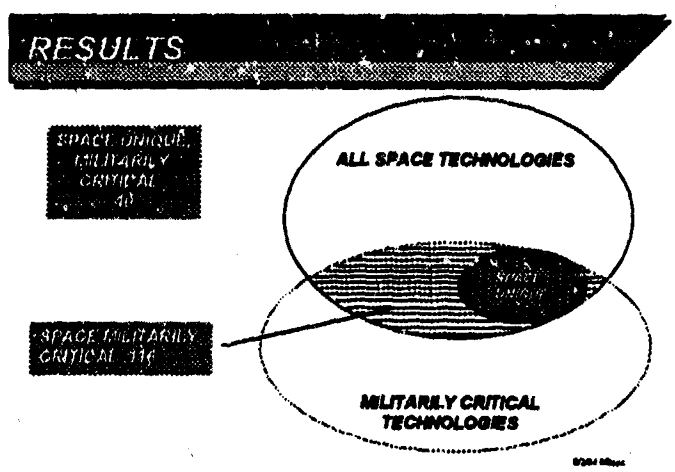
## G. CONCLUSIONS

The SSTWG study concluded:

1. All Services need an **integrated space mission area "road map"** to provide a firm basis for space technology planning and prioritization. Space technologies are not adequately recognized as an individual category in the MCTL and in key DoD planning and funding documents.

2. Modifications to the development process techniques of systems engineering and integration (SE&I) as applied to space systems (defining, developing, manufacturing, integrating, testing, launching, and on-orbit operations) have significant potential for greater efficiencies, cost saving, assured access to space, and continued U.S. space leadership.

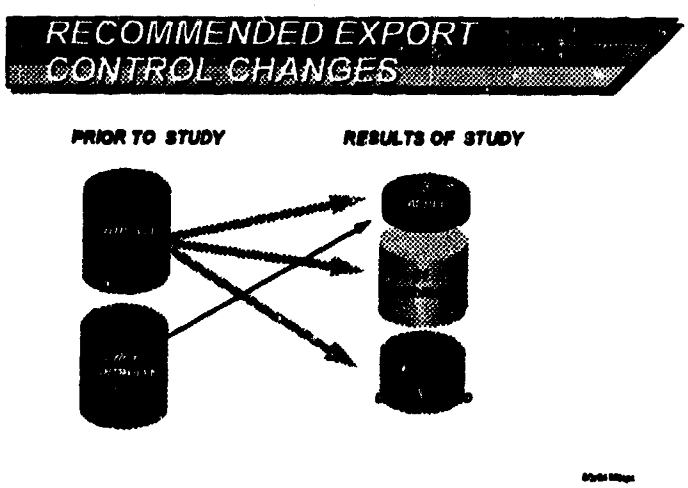
3. Forty technologies of the 116 militarily critical space technologies, have been identified and categorized as critical space unique and should be recognized as such in the appropriate DoD documentation.




Of these, 37 are dual-use. These dual-use technologies require more precise and explicit parameters to ensure that only critical items are controlled and those outside the explicit parameters are made available to the open commercial market.

Thirty-six technology areas that have high payoff potential and are candidates for additional investment have been identified.

Sixty-one technologies were recommended for a change in their export control status: 27 of these were recommended for decontrol; 31 were recommended for less stringent control; and 3 not currently controlled were recommended for control.




Sixty-three technologies have been identified as candidates for partnerships through CRDAs and specific international agreements (MOUs).

4. **Payload modules, buses, and interfaces must be standardized** to improve technology insertion and provide improved interoperability and savings within the military and commercial space community.

5. **Selling the products of space technology or on-orbit capabilities** rather than selling the specific technology has the significant potential of **protecting the U.S. job and production base** and the associated development and production technologies. This practice has already begun with the Global Positioning System (GPS) services and high-resolution space imagery products ($400 million in 1993 and a potential $2 billion in 2000).

*These space technology areas are treated in more detail in the "Technical Report," IDA Document D-1521. Summary tables of each technology area are included in Section III of this document.*

## H. RECOMMENDATIONS

Based on these conclusions, the SSTWG makes **the following recommendations**:

1. **Space systems technologies** should be included as a separate, unique section in all future versions of the MCTL.

2. **Key DoD planning and resource documents** (such as the Defense Science and Technology Strategy and the DoD Key Technology Plan) **should treat space technology as a separate, unique area.**

   Specifically, DoD should create an integrated space mission area road map to provide a firm basis for space technology prioritization and development.

3. An existing advisory board, such as the Defense Science Board (DSB), should **identify SE&I practices** that have been successful in other key industries and that can be applied to space programs.

4. The United States should **include unique critical space systems technologies in the new international export control regime and incorporate recommended changes.**

5. **Where beneficial, the United States should pursue both domestic and international partnerships through CRDAs and MOUs for identified space system technologies to bring these technologies into production sooner and at lower unit cost.**

6. **DoD should take the initiative** for the government and industry in **defining interface standards and should encourage standardization for launch vehicle payloads, payload interfaces, and modular space components.**

7. The United States should **emphasize selling complete space systems or using the products** of space technology rather than selling the development and production technologies themselves. This practice would improve the U.S. job outlook and protect the critical technologies involved.

**Implementing these recommendations will provide impetus and rationale for ensuring that unique space-critical technologies are adequately recognized and that the necessary investment is made *now* to ensure that the United States continues its leadership in military space capabilities into the 21st century.**

## I. REVIEW PANEL

The following page lists the members of the SSTWG Review Panel.

**SSTWG REVIEW PANEL**

Both the SSTWG Scripted Briefing and the Executive Report have been revised to reflect the comments and recommendations of the senior review panel.

As suggested by the panel during the 16 Feb 94 meeting, the signatures below indicate that the panel members have reviewed this SSTWG Study Executive Report and believe the conclusions and recommendations of the Study are sound and will assist in assuring that critical space technologies are recognized and properly supported and that this will help the United States maintain its military capability leadership.

Brig/Gen Roger G. DeKok
Director of Plans for Air Force Space Command

Lt/Gen Lincoln D. Faurer (USAF Ret)
Aerospace Consultant

Dr Robert J. Hermann
Senior Vice Pres Science & Technology - United Technologies Corp.

Lt/Gen Donald L. Cromer (USAF Ret.)
President Hughes Space & Communications Co.

Maj/Gen (Dr.) Donald L. Lamberson (USAF Ret)
Aerospace Consultant

Dr. Charles W. Cook (Senior AF Civ Ret)
IDA Consultant - Ex AF Dep Asst Sec for Space Plans & Policy

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# I. INTRODUCTION

Space is a unique environment that provides unparalleled military operational advantages and economic opportunities.

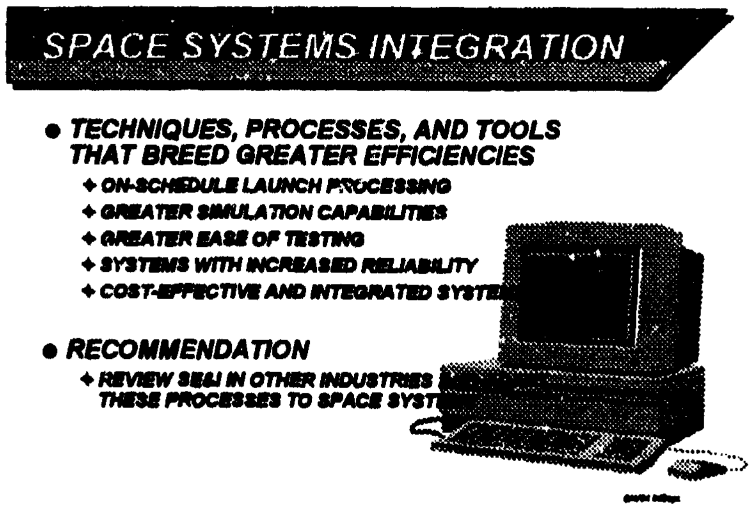
The importance of space and space technology to provide **global reach** and **global power** is captured in the statement by Air Force Secretary Widnall: ***"Control of space and access to it are fundamental to economic and military security."*** To the military commander, space provides the advantages of viewing areas of interest, knowing the weather, being able to navigate and accurately locate areas of concern, and the ability to execute command and control of operational forces anywhere to support national security goals and objectives.

To withstand the space environment, components must operate in conditions of extreme thermal cycling and are exposed to radiation. Reliability requirements are measured not in days but in years. This environment requires **unique space technology parameters**. The bottom line is that the unfriendly environment of space and its impact on space systems, be it out-gassing, high-energy particle bombardment, radiation damage, atomic oxygen reactions, or the long-life requirements of space components, is a significant technological challenge.

Many of the space-unique technologies have both military and commercial uses. The few that are judged militarily critical will provide the United States with the capability to maintain its military leadership role in space for years to come. These technologies should be recognized and given special attention. Section II discusses the specific technologies that are identified as "space critical." Section III gives additional information about each of these technologies.

# II. CRITICAL SPACE TECHNOLOGIES

## A. SPACE SYSTEMS INTEGRATION




SE&I technology involves the *process* of **defining, developing, manufacturing, integrating, and testing a cohesive system of ground, launch, and space segments from design concept and on-orbit operation through disposal.** For space systems, this *process* is very **lengthy, costly, and, for many of the processes, inefficient.** Improvement in the SE&I "process" has the potential for large payoffs in **developing and using critical space technologies.** Significant improvements in SE&I will play an **important role** in maintaining the ability of the United States **to be competitive** in the world market.

One of the recommendations is that **an existing advisory board, such as the DSB, review and study of the latest worldwide SE&I concepts and processes available, particularly in the automotive and electronics industries.** The results of this review should recommend a way ***to develop optimum SE&I processes, techniques, tools, simulations, and models to support space technology development and production.*** **Improvements in the efficiency of space systems' SE&I processes are essential if the United States is to retain world space system leadership and reduce costly, extended development as,** for example, has been the case in the MILSTAR program.

In the future, it is envisioned that technology development and funding will follow one or more of five broad concepts: (1) **cost-shared** research and development; (2) **cooperative partnerships** between government and industry; (3) **support of**

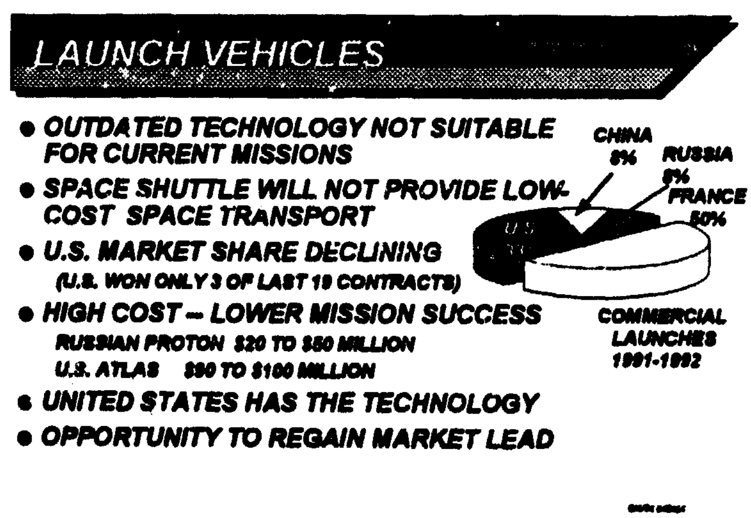
commercial research and development (R&D) by the DoD laboratories; (4) **focus on dual-use** technologies development; and (5) **an expanded** Science and Technology **Reliance program.**

Examples of process and technology items that have dual-use application are improved radiation hardness compliance capability; fault tolerance; autonomous operations via artificial intelligence (AI); space debris identification for cataloguing; launch vehicle processing; electromagnetic compatibility (EMC) and lightning protection; standardized interfaces; a system design and synthesis process **integrated** with a system requirements analysis process; **systems engineering processes,** including automated tools and metrics; and **integrated weapons systems management.** One of the most important emerging space technologies is self-testability, with a built-in-self-test (BIST) capability designed for all components and at system levels, including an autonomous and robotic system design, to permit easy ground operational monitoring. Advanced autonomous systems designs include BIST and self maintenance and high-reliability features.

Section III of **this document** identifies critical processes and technologies that should **be improved,** those that could **be used in joint program ventures,** and some that should **be funded by the government to improve U.S. competitiveness** and market position in the international arena

## B. LAUNCH VEHICLES

The Delta, Atlas, and Titan expendable boosters have been the backbone of our space lift capability and will continue in this role into the 21st century. However, these launch vehicles were designed more than 30 years ago and their technology is now outdated and expensive to operate. Although the space shuttle was envisioned the workhorse that would provide low-cost space transportation, this goal has not been and will not be realized.



With the fall of the Iron Curtain, Russia has joined the competition for providing a low-cost, highly reliable launch capability along with France, Japan, China, and Brazil. Overall, the U.S. market share of space launches has decreased significantly since the 1980s. The impact of this trend is highlighted by the **fact that the United States has won only 3 of the last 19 space launch contract opportunities.** France provided 50 percent of all worldwide commercial launches in the 1991–1992 time frame. This situation has occurred because of a French investment strategy that has made their space launching more cost effective and efficient.

To compare competitive costs for U.S. launch services, launching a satellite with the Atlas system costs $90 to $100 million. Launching a comparable load with an Russian Proton missile costs only $20 to $50 million. The flight reliability of these systems is difficult to verify.

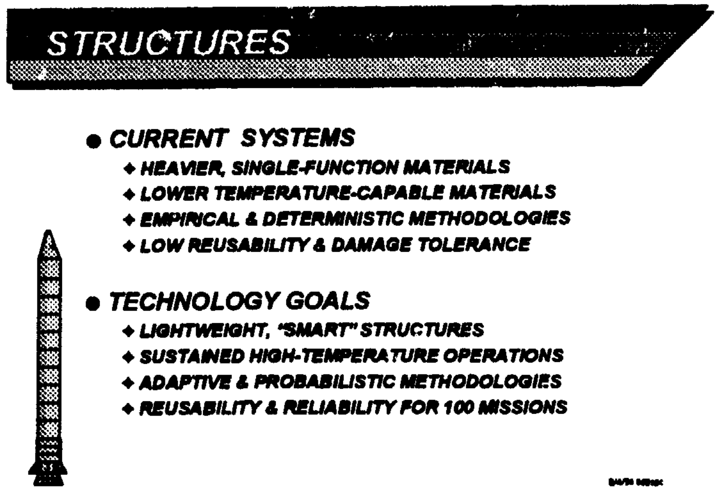
**The United States has the intrinsic capability to advance technology and regain the world space market lead.** Space-critical technologies should be nurtured, and, in some cases, protected as **space-critical technology items to ensure U.S. military and economic leadership (see Section III).** Continued work in critical technologies, such as fault-tolerant avionics, automated launch control systems, and electromechanical and hydraulic systems, has the potential to reduce costs and increase launch system reliability.

To reduce the time and cost of vehicle payload integration and launch and to remain competitive in the world market, the U.S. government and industry **must standardize interfaces** for the launch vehicle to the payload bus and employ new **advanced technology-based launch vehicles in order to reduce the infrastructure and personnel requirements which are the most significant factors**. These technologies have significant payoff in modernized, near-term expendable systems and in the more challenging reusable and single-stage-to-orbit systems of the future.

## C. STRUCTURES

The United States continues to lead the world in the development and production of aluminum-lithium (Al-Li) alloys and composite structures such as graphite-reinforced thermosets and thermoplastics and metal matrix materials. **However, Europe and Asia are now challenging this U.S. lead.**

Applying this technology to satellites and launch vehicles can provide **weight savings of up to 60 percent,** with significant (greater than a factor of two) **reductions in cost and fabrication time.** Using lightweight, high strength-to-weight ratio materials that are dimensionally stable and have minimal out-gassing properties will be required to meet future space structure needs where weight reduction is a driving issue.




**Continued work in structural control and system monitoring technologies will provide critical data for new models and simulations, resulting in improvements to all launch vehicle technologies.**

Structural control technology is being developed to achieve higher pointing precision and finer control. This will allow the United States to more accurately track targets and provide better stable vibration-free platforms for space sensors and laser cross-link communications.

**Space systems health monitoring technology** is being developed for use in separating space packages and for maintaining space systems once they are in orbit. This technology includes advanced methodologies for determining and sensing the actual structural parameters that define the response of the system, analytical models that accurately use the parameters to predict response, sensing systems to measure structural response, and control systems that could include neural networks to respond to system changes.

**Most space structures technologies are considered dual-use, for which export controls are not recommended.** Instead, space structures technologies lend themselves more to **cooperative programs where the costs and benefits of new developments can be shared and where both military and commercial benefits will accrue.**

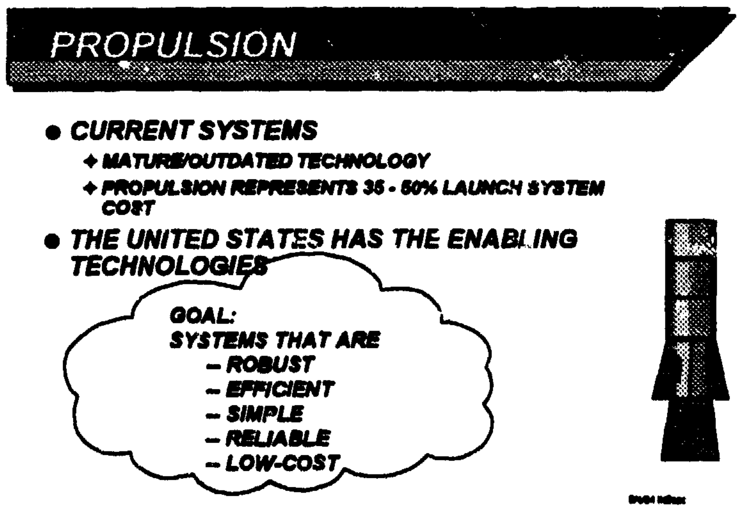
The main area of concern for militarily critical space structures technology is the **manufacturing and process techniques** for advanced materials with embedded sensors

that can detect and control vibration to less than 10 nanoradians angular pointing accuracy. **These manufacturing and process techniques should be controlled.**

The critical space structures technologies requiring additional funding include smart structure controls, advanced low-weight-to-stiffness alloy and composite development, and structured system health monitoring.

## D. PROPULSION

The space systems described in Launch Vehicles are based on **old, expensive intercontinental ballistic missile (ICBM) technology.** These propulsion systems have moderate-to-high reliability but also have **high** operating costs. They are 35 to 50 percent of the total missile system costs and contribute greatly to **pricing the United States out of the world launch market.**




**The United States has the enabling technologies to lead in low-cost propulsion systems.** However, we lack **national priority and resource support to develop these technologies for the next-generation propulsion systems and launch vehicles.** In addition, the availability of modified ICBM boosters and the existing infrastructure have contributed to this situation. The goal of these enabling technologies is to provide robust, efficient, simple, **highly reliable, low-cost propulsion systems that meet critical military launch requirements and also allow the United States to compete in the commercial launch market.**

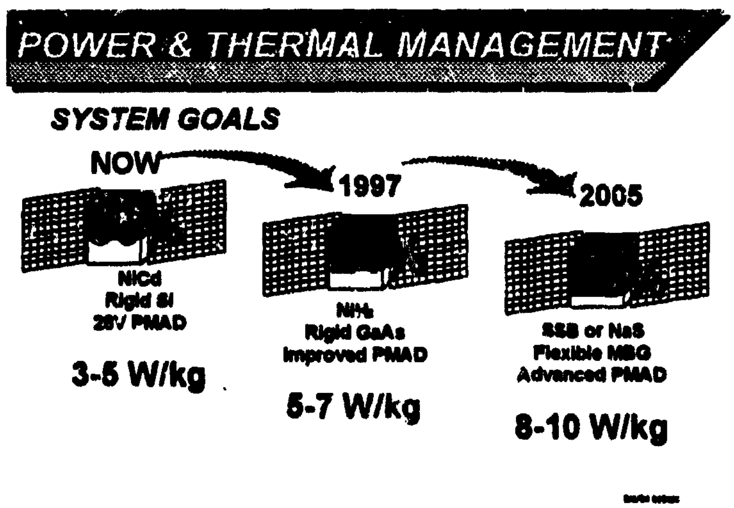
Emerging critical propulsion technologies are grouped in three basic categories: **chemical** (which includes liquid, solid and hybrid systems), low-thrust **electrical,** and **nuclear thermal.** Electric propulsion can provide efficient station-keeping and maneuvering capabilities. Each of these technologies has considerable potential, and R&D must be continued. Future rocket and missile systems will use all of these propulsion technologies in one form or another.

Low-cost solids and low-pressure, high-tolerance liquid propellant systems or hybrids are the leading candidates to meet our currently projected first stage propulsion needs. Nuclear thermal propulsion appears to be very attractive for high-energy upper stage propulsion and for co-generated electrical output systems; however, it must overcome additional environmental challenges to reach its full space potential.

Most propulsion technologies are dual-use and have direct commercial applications. Propulsion technologies needing export control are those that apply to ballistic missile proliferation. To offset these controls, the United States should be prepared to sell the launch or on-orbit service provided by this new technology. The sale of these services will not only improve the U.S. position in the world launch market but will reduce the desire of other nations to develop their own capability or seek services elsewhere.

Dual-use propulsion technologies that need additional resource support to reach maturity include high-energy density propulsion materials, improved propellant bonding, and advanced cryo-cooling and storage.

## E. POWER AND THERMAL MANAGEMENT




Power and thermal management are key technologies for effective use of the space environment. Taken together, the Environmental Protection System (EPS) constitutes 10 to 30 percent of spacecraft weight. New power and thermal management technologies must be supported if the United States is to maintain its competitive position in the world market.

Future space applications, both commercial and military, will require high power (greater than a kilowatt), long duration operation (greater than 3 years), and controlled operating temperatures for spacecraft hardware. These demanding requirements lead to a preference for passive systems that operate maintenance free, provide

heat rejection by radiation, require low mass and volume, and are capable of reliable autonomous operation. Power generation, other than photovoltaic, requires **thermal management** at high temperatures while sensors, electronics, and crew support require thermal management at moderate-to-cryogenic temperatures.

Solar cells mounted on the surface of the spacecraft or deployed on solar arrays are highly reliable and **account for the majority of power generation systems** flying today. Today's state-of-the-art cells include lower cost **silicon (Si)**, which is 13 percent efficient, and more radiation-resistant **gallium arsenide (GaAs)** with efficiencies of up to 19 percent. Advanced cells, including **thin-film, poly-crystalline** (or amorphous) **silicon,** and **multi-band-gap (MBG)** cells, are being developed to lower cost, increase efficiency, and provide higher radiation resistance. **The United States currently leads in most solar cell developments.**

Dynamic conversion of solar energy offers the potential for **high efficiency** and reduced drag in orbit. Solar energy, focused into a heat receiver, heats a working fluid. The working fluid drives a heat engine, using either a Brayton, Rankine, or Stirling thermodynamic cycle. This engine, in turn, drives an alternator that converts the heat into electrical energy. ***The system-specific power (W/kg) of solar dynamic conversion is currently not competitive with photovoltaic systems, as is shown later in Section III. Continued work is needed in these technologies to achieve high efficiency and reduced-weight power conversion systems.***

Nuclear power systems have high power densities, operate independently from orbit position (eclipse, distance to the Sun), and have **potentially long operating life and growth potential.** Two nuclear candidates are nuclear fission reactors and radioisotope systems.

Nuclear fission reactor technology has **high theoretical promise for space applications** but requires significant continued development. Long, unattended operations with **high reliability and autonomous control are required,** and operating temperatures are high. Compact designs will require effective shielding and radiation-hardened sensors.

Radioisotope systems, up to a few hundred watts, have operated reliably in space for decades on a total of 23 U.S. space missions.

Batteries for power storage typically comprise 10 percent of the total spacecraft dry weight. Nickel-cadmium (NiCd) and nickel-hydrogen ($NiH_2$ or $NiMH_2$) batteries are

state of the art. New developments include sodium-sulfur (NaS) and solid-state polymer (SSP) batteries. The Japanese have taken the lead in SSP batteries because of anticipated commercial applications. The graphic on the previous page describes the future power and thermal management system technology goals.

Thermal management is critical to spacecraft design and includes the development of **microchannel heat exchangers, cryogenic refrigerators (cryocoolers) and heat pipes** that have an effective thermal conductivity several hundred times that of the best metals and have no moving parts. In space, because of the rejection of heat only by radiation, the development of carbon-carbon (C-C) radiators and lightweight heat transfer technologies is very important and requires further R&D.

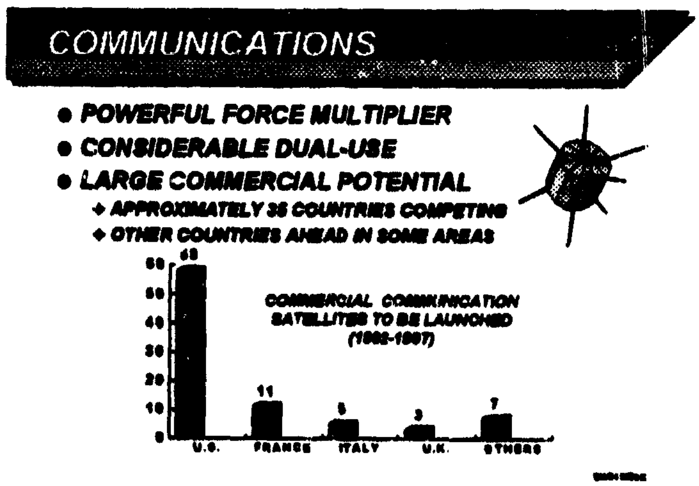
Most space power and thermal management technologies are **dual-use.** Technologies that make the power system (and the spacecraft) more **survivable against man-made hazards are likely to be unique for military systems.** Some long duration commercial spacecraft may require hardening against pellets, ultraviolet (UV) radiation, and natural space radiation.

Most power and thermal control system technologies are produced and marketed internationally for both commercial and military applications. To be economically viable, technologies being developed in military programs **may require an unrestricted market *or* government-subsidized production to provide the stimulus for advanced commercial development of these new technologies. This was the case in the early development of communication satellites.**

**Dual-use technologies that need additional support to reach maturity include high-specific-power photo-voltaic cells, high-energy density batteries (recyclable over 1000 times), and high-efficiency cryocoolers.**

## F. COMMUNICATIONS

Space communication is a **powerful force multiplier** and is critical to modern military operations. With the boom in telecommunication products and services, **telecommunication applications continue to be on the forefront of military advances** and are mandatory to maintaining

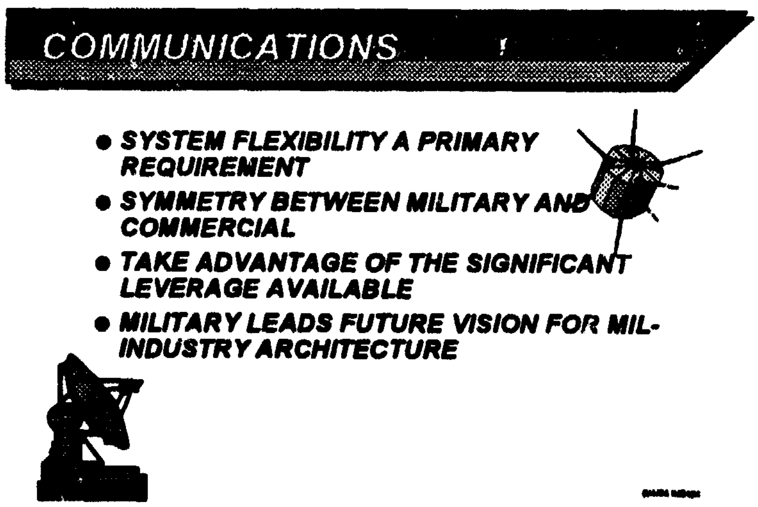


a superior force. Correspondingly, the **dependence on space communications has steadily increased.**

Some military needs are unique; however, **most space communications technologies are dual-use.** Approximately **35 countries have space programs,** and the predominant emphasis is in communications. A significant number of these countries are trying to become a leading developer in the space communications industry. The United States is the dominant country in space communications; however, several countries and multinational alliances are competing technologically with U.S. industry in many areas of space communications.

**Unique space-critical technologies** need additional support in the following subsystems: **adaptive nulling, integrated phased array and large multibeam antenna systems, solid-state amplifiers, and gigabit (Gb) rate receivers.**

System **flexibility and accessibility** are very important. Even with the increased capacity of fiber optic communications, **space communications** will still be needed to fill the communication **gaps** of land-based systems. Satellites have this flexibility in all regions of the world.



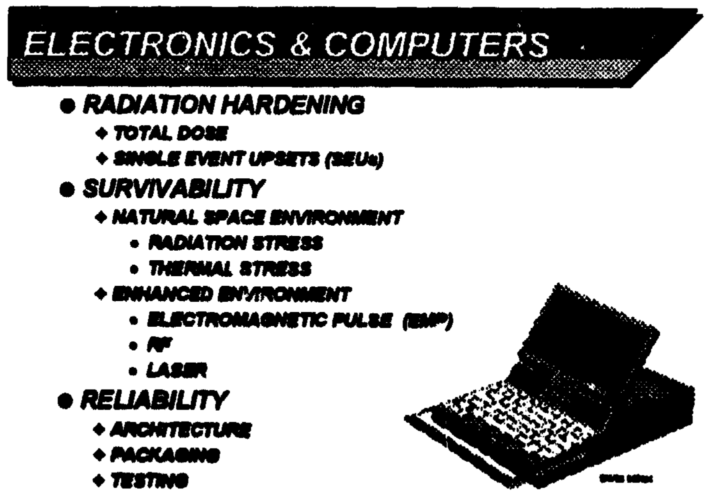

Space communications is still overwhelmingly a government sector activity. The vast majority of the world's investment in space communications (more than 60 percent) comes from government funding. As the space communications industry matures, this percentage could change, but space investments currently seem to lie outside the financial planning horizons of most companies. The U.S. commercial sector has depended to a great extent on the government and military work to support their R&D. With the reduction in government support for military satellites, companies have experienced a corresponding reduction in R&D investments for potential commercial satellite technologies.

The U.S. military will continue to be a dominant user and developer of communication satellites. In this position, the U.S. Government can use this leverage to assist the U.S. commercial sector in technology advancement and significant manufacturing improvements. For example, standardized modular designs provide flexibility while achieving considerable development improvements.

If the U.S. Government took the lead in **standardizing a future modular architecture** for all communication satellites, this action would allow the potential for cost sharing and a U.S. competitive advantage. A **modular architecture** derived from the military to assist industry in technology advancement and provide commonalty could reduce engineering and development costs in many sectors of the space industry. Accomplishing this goal will require a partnership to further the capabilities of the military and industry. This partnership has the potential to provide the improvements in the civilian economic competitiveness in communications that are needed to maintain our global position in space communications developments. It also could be an important element in capturing the expanding third world market and is of great interest in Iridium-type direct satellite communications systems, where literally hundreds of satellites are involved.

## G. ELECTRONICS AND COMPUTERS

Most space electronic and computer components perform the same function as that of their nonspace counterparts. However, space electronics and computer components must be **highly reliable and radiation hardened.** The graphic depicts the critical elements of space electronic and computer technologies.




**Radiation hardening** of electronic components and their design for survival against electromagnetic pulse (EMP), strong radio frequency or (RF) waves, lasers, and the natural space environment—when combined with **high reliability**

and low power, volume, weight, and *cost*—present a severe challenge for space electronics and computer technology.

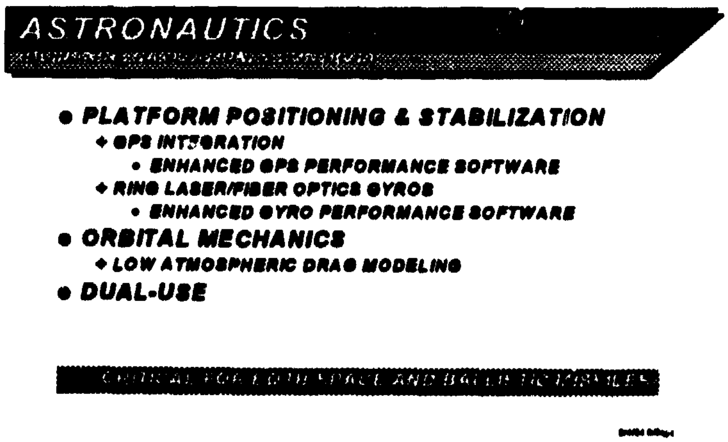
**Reliability** is a very critical requirement for space electronics and involves a number of important technologies, including the overall architecture of adaptive and redundant system design, packaging technologies, and testing technologies.

Important **ongoing technology** developments that **must be supported** are **hardened digital processors, packaging of monolithic wafers and hybrid wafer scale integration (multichip modules), and three-dimensional (3D) packaging**. Fault-tolerant computing, optical processing, and opto-electronic integrated circuits are also important space technologies. Radiation hardened micro-electronic-mechanical systems (MEMSs), which are a class of sensors that respond to physical stimulus and transmit electrical impulses for interpretation, measurement, or operation by a control system, are **vital to advanced space systems.**

Virtually all electronics and computer technologies used in space have a ground-based or a **civilian space-based counterpart and are, therefore, dual-use. However,** two military areas, **strategic radiation hardening** (nuclear weapons environment) and **extraordinary survival technologies** (space weapons environment), **have no ground-based or civilian space-based counterparts.** ***These technologies should be protected from unrestricted export.***

**Dual-use technologies that need additional support to reach maturity include improved radiation hardening; lightweight, high-efficiency electronics; (3D) packaging; fault-tolerant, high-speed computer hardware; and very high reliability electronics and computers for flights of 10 years or longer in duration.**

## H. ASTRONAUTICS (GUIDANCE, NAVIGATION, AND CONTROL)




Ballistic missile accuracy depends on inertial space platform navigation and guidance system technology. Military satellite sensors and laser communication crosslinks (which must have high data rates with a low probability of intercept) require precision astro-nautics. Third World

countries want this technology and **as many as 15 countries already have operational ballistic missiles.**

Recent technology developments (GPS, fiber optic gyros, and software algorithms) make simpler, less expensive, and **highly accurate** guidance components available **to many countries.** The gyroscopes, accelerometers, and accompanying technologies required for the stabilization and navigation of the satellite while on orbit are approximately the same technologies used to launch the satellite (or a ballistic missile) into orbit. Also, this same basic astronautic technology is used for civilian applications such as commercial aircraft and ship stabilization and navigation and for peaceful space applications such as weather and communication satellites.

The **dual-use capability characteristic of astronautic technology elements, items, and systems presents a serious problem for participants in today's global space market.** Many times, countries purchase technology for legitimate purposes, but some countries (as demonstrated by pre-Gulf War Iraq) retro-engineer, copy, or directly divert technologies that are considered to be tightly controlled.

A critical example of dual-use technology is the **readily available GPS**. The GPS was developed to provide military land, sea, and air forces with their precise location on the earth and in low aerospace. The use of GPS in civilian applications is increasing.

The GPS can be used to enhance satellite guidance and attitude performance. Unfortunately, the GPS has **potentially dangerous applications** such as **an inexpensive ballistic missile guidance system.** Although DoD has incorporated a "war mode" into the GPS that decreases the accuracy of the system, **several techniques (through software and hardware) allow a large portion of this inaccuracy to be removed. More than 300 versions of GPS receivers are sold throughout the world. A similar system is Russia's Global Navigation Satellite System (GLONASS).** Although GPS is now fully operational, the Russians have not completed the necessary orbital portion of their system. However, receivers are being built to receive signals from both systems to resolve ambiguity and loss of signal that may occur with either system.

**Dual-use technologies such as advanced gyroscopes, accelerometers, and accompanying technologies need cooperative agreements with industry to achieve the required improvements.**

Control of the militarily critical elements of astronautic technology is difficult. The current MCTL includes but does not adequately define many of these technologies. One

approach to controlling this predominately dual-use technology is to emphasize the sale or use of our technology products in complete vehicles or on-orbit capabilities where value added by the United States has been maximized and reverse engineering is difficult.

## I. SENSORS AND SURVEILLANCE

**SENSORS & SURVEILLANCE**

- ***"CROWN JEWELS"--VISIBLE AND INFRARED (IR) SENSORS***
  - ***REAL-TIME DIGITAL DATA COLLECTION***
  - ***INTEGRATED ARCHITECTURE -- RAPID DATA TRANSFER***
- ***MANY DUAL-USE SENSORS -- HARD TO PROTECT***
  - ***VISIBLE & NEAR IR: ELECTRONIC PHOTOGRAPHY, HIGH-DEFINITION TELEVISION (HDTV)***
  - ***IR: FIRE, RESCUE, POLICE, MANUFACTURING***
- ***FOREIGN COMPETITION***

Existing controls have allowed the United States to maintain **a lead in space sensors**. Emerging technologies provide the **potential** to **maintain this lead.** However, new technologies such as optical memory devices, programmable chips, high-resolution vidicon tubes (where competition is strong, particularly from the Japanese), and focal plane arrays (from Japan and France) are **challenging our ability to maintain this space sensor technology lead.** An expected **large market exists for high-resolution vidicons for high-definition television (HDTV).**

These new technology challenges, combined with reverse engineering and cannibalization of existing systems, compel the United States to **support the emerging technologies** and to control existing critical technologies. Long wave infrared (LWIR) sensors that provide high signal-to-noise (S/N) ratios with very low noise background at cryogenic temperatures must be developed to image cold objects against a very cold background. These LWIR sensors are required to detect and identify debris and space objects.

Current electro-optic and infrared (IR) sensors allow the United States to examine activity at any point on or near the earth. The electronic readout capability of the newer sensors gives the satellite an essentially **indefinite life on station** as compared to earlier systems that used film and were limited by the magazine size. In cases where scattered sunlight or thermal radiation is not adequate to form images of sufficient detail and clarity, laser illumination can be used. These capabilities are central to the U.S. early warning capability for missile launches and locating nuclear detonations and are also a major component of tactical and strategic data collection.

**Some critical astronautic technologies are as follows:**

- **High-resolution, space-qualified charged coupled device (CCD) arrays** and large (8192 element or greater) linear detector arrays that allow electronic readout of image data from the ultraviolet to near infrared (1.2 microns) spectral region. **A detector with a resolution element spacing of µ 3 m would allow a resolution equivalent to a good, fast high-resolution film such as Kodak Tri-X. This is the technology of choice for imaging space cameras in satellites and for ground- or aircraft-based devices for space object identification.**

- **Space-qualified, IR sensors,** which are the key element in sensor systems, such as the Deep Space Probe (DSP), that monitor missile launches. A major concern is whether the **sensing element and the cryogenics to support it will function reliably in space with unattended operation for 5 to 10 years.**

- **IR detector arrays, often called focal plane arrays (FPAs),** including one dimensional (1D), two dimensional (2D), or three dimensional (3D) arrays enable imaging analogous to the vidicons in the visible spectrum. While a vidicon responds to light wavelengths generated as scattered sunlight or man-made radiation, the IR array responds to the heat radiation emitted by the sunlight or by other hot or warm objects. The reduced spatial resolution (because of the long wavelength) is offset by the improved contrast to the background for heat engines, the **ability to "see" at night, and an improved ability to penetrate cloud cover.**

- **Active sensors, including radar and ladar, which provide decisive improvements in support to theater forces.** Day/night adverse weather theater surveillance by radar will improve command, control, communications, and identification ($C^3I$) on the battlefield. Ladar can improve weather information and imagery. Dual-use potentials are more limited for active sensors.

Space-qualified, high S/N arrays (greater than 50,000 elements) for long IR wavelengths may need to be controlled because of their strategic importance. However, since most military space sensor and surveillance technology **is dual-use, the same IR detectors may have many terrestrial** applications. Currently, both "space-" and "nonspace-qualified" IR detectors are embargoed because of Army terrestrial requirements.

**A dual-use example** of astronautic technology is the Hubble Space Telescope, which is a reconnaissance camera looking up rather than down. Now that spherical

aberration is corrected, Hubble could function as an "embargoed sensor" for some militarily critical applications and as a classic universe exploring telescope. The United States should continue the present sensor and surveillance export control limits, **with constant upgrade and review, to attempt to allow the maximum latitude for** the development of scientific and earth resource space-based sensors (as well as ground- and space-based astronomy) **consistent with protection of critical defense technologies.**

One approach, mentioned earlier, to controlling this predominantly dual-use technology is to emphasize **selling the products of our technology in complete vehicles or on-orbit capabilities where value added by the United States has been maximized and reverse engineering is difficult.**

## J. OPTICS

**OPTICS**

- *LIGHTWEIGHT SPACE OPTICS*
- *ADAPTIVE OPTICS*
- *COOLED, HEL OPTICS*
- *UNCOOLED, HEL OPTICS*
  - *LOW ABSORPTION COATINGS*
  - *SINGLE-CRYSTAL SILICON*

Optical components and their related technologies are very important to the U.S. **military and commercial** space capabilities and the space industry. Optics are critical elements of surveillance and reconnaissance satellites. They set **the limits of possible target detection, identification, and resolution.**

Optical components are also critical elements in projected space-based High-Energy Laser (HEL) systems. If these optics do not have the proper figure (shape) and finish (polish) and cannot survive operational power levels, the laser system cannot perform as required. Low-power, **relatively large optical elements are required for space power, relay, and communication systems.**

Another critical optics area is the projected **manufacture of optical elements** or **materials in space.** This includes manufacturing membrane or lightweight optics (that are either **too large or fragile to be launched** from earth) and **processing** optical materials in space.

**Four areas comprise the critical space optics technologies process:**

1. Design of the optical systems and components
2. Production methods for highly accurate, lightweight optical components
3. Specialized exotic materials used for the optics
4. Precision meteorology associated with the fabricating and certifying space optics.

Space optics also can be classified as **cooled or uncooled. Cooled optics** are most commonly used in exclusively **military HEL applications. Uncooled optics** fall into two basic categories. The first category is low-absorption coatings for **mirrors used for surveillance**, reconnaissance, acquisition, pointing, and tracking and those used for **communication applications**. Most of these optics require high-reflectivity coatings or partially transmissive or selective wavelength coatings. Many of the optics in this category are dual-use. The second category is the **advanced transmissive component** typified by **single-crystal silicon optics.**

The combination of a **substrate** that is transmissive at the application wavelength and a very **low absorption coating** allows the use of **uncooled** optics for HEL application. This relatively new technology **represents a breakthrough in optical component development for HEL systems** (specifically, space-based HEL applications) because it substitutes very expensive, complex, heavy components **with lightweight, inexpensive components.**

***Optics in the second category of uncooled optics are currently used exclusively in military applications and must be protected for both space and terrestrial applications. In addition, the development and production technology for large phased array deployment and control are space unique and critical for HEL military application.***

**Most optics have dual-use.** Nearly all optical systems in space can be used for both military and commercial applications. For example, surveillance satellites are used for military observation and for mapping natural resources, evaluating environmental effects, and conducting astronomical studies. Space communications and the manufacture of optics and optical materials are also areas of **potential dual-use. Reconnaissance and directed energy weapon (e.g., space-based laser) applications are uniquely military.**

Optical technology has seen **more progress in the past 30 years than during any other** comparable time period. Laser technology and modern computers have

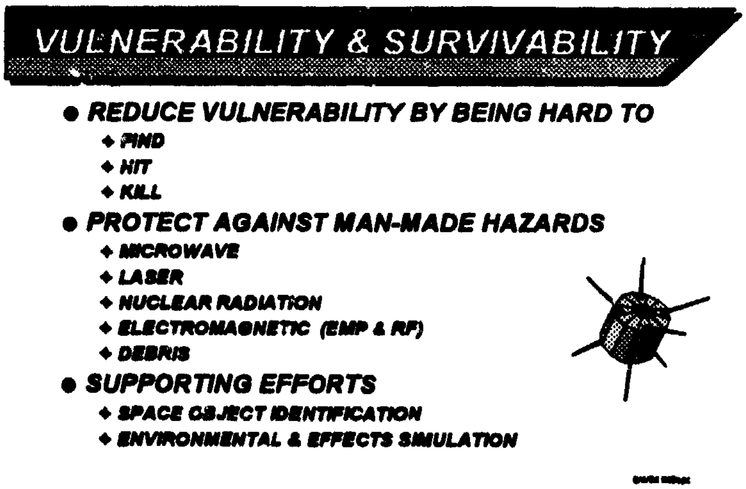
radically expanded the number of applications for optical components and have revolutionized the measurement and fabrication of optics. This revolution in optics has occurred for defense-related components and systems and for commercial products and applications.

The United States, Japan, and most Western European countries have well-developed capabilities in optics per se but less capability in dedicated advanced space optical systems and components. **The United States must balance the need for allowing industry to compete in the expanding optical components and technologies world market and for protecting military interests.**

**The primary technology requiring additional support and development is the radiation and atomic oxygen hardening of optics and their coatings.**

## K. VULNERABILITY AND SURVIVABILITY

**Survivability** of space systems covers the technologies associated with **protecting or hardening** these systems as they perform designated missions in **natural** or **man-made hostile environments.**




The vulnerability of space systems is reduced by making the systems **hard to find, hard to hit, and hard to kill.**

Technologies that **suppress and control signatures**; techniques for **deception, proliferation, and reconstitution; and use of off-orbit spares** are important to enhanced system protection for the "hard-to-find" cases. Technologies such as **autonomy, maneuverability, attack warning, and use of decoys** are important for the "hard-to-hit" cases. Technologies such as **hardening to nuclear, laser, RF, kinetic energy weapon, and debris environments** are important for the "hard-to-kill" cases. The **mission-critical space system components** that are important to radiation **harden** include sensors, processors, communications components, attitude control systems, power systems, structures, and propulsion systems.

**The importance** of protecting space systems against natural and man-made hostile environments **must not be minimized.** Developing and placing a space system in orbit and repairing or maintaining this system in orbit—if this is possible—are very costly. In the past, equipment designs have included protection features that resulted in a **military-unique system.**

**Dual-use technologies** are being encouraged, if not demanded, because of the need for **economic leverage.** Consequently, the United States must **evaluate the controlled technologies** and processes very carefully to meet military system needs **without limiting** the ability to take advantage of the **lower cost** commercial technology being developed.

Many of the military and government **hardening protection technologies appropriate for the natural environments must be considered for commercial applications.** Commercial and military systems must survive in many of the same **natural** environments, and many times the military depends on **commercial systems** (e.g., space communications). Therefore, these dual-use technologies **should be shared, where practical, to enhance the survivability and reduce the costs of military and commercial systems.**

Identifying the **critical vulnerability and survivability technologies** is the result of an orderly process **(see the "Technical Report," IDA Document D-1521)** that relates specific space system characteristics, missions, and capabilities to the known threat environments, damage mechanisms, and **protecting designs and technologies.**

Technologies that are **militarily unique** relate to the **hostile man-made space environment,** which includes nuclear radiation, electromagnetic susceptibility, EMP, high-power RF, microwave effects, laser effects, space debris, signature and signature control, and space object identification. Some of these survivability technologies are common to both military and commercial space systems.

Two identified military critical technologies that ***must be protected*** are **filters that limit high power RF energy** while passing the wavelengths of the sensor signal and **processes and algorithms that identify foreign spacecraft by using their signatures.**

## L. QUALIFICATION AND TESTING

Space qualification and testing **is the bridge** between designing and manufacturing a system to meet a specific mission profile and the **verification and assurance before launch** that the system **will function properly.** Qualification and testing technologies include advanced measurement or metrology techniques, environmental test facilities and simulation, system design response and environmental prediction models, data collection and analysis systems, and test engineering tools and practices.


The **United States leads in sophisticated** space qualification and testing **capabilities, but not in cost-effective, automated testing and launch processing,** which the French currently are using with the Ariane V.

The basis of a space system test program is the **natural** and **induced environment** to which the system will be subjected during manufacturing, assembly, shipping, pre-launch, launch, ascent, and on-orbit operation. Test levels are based on **worst case predicted levels** with minimum stress levels adequate to detect and **screen infant mortality failures.** Hardware testing is conducted throughout the **entire manufacturing process** starting with the raw materials and piece parts through the total system level. A typical DoD satellite system may require **1 to 2 years of system level testing.**

The **natural space environment** includes system exposure to vacuums, magnetic fields, trapped radiation, solar particles, cosmic rays, atomic oxygen, upper atmospheric drag, micrometeoroids, thermal radiation, and zero gravity. **Induced space system environments** include effects caused by ground processing, transportation, handling, storage, launch injection, debris, and weapons system radiation.

Space system test programs, **regardless of the customer** (military, National Aeronautics and Space Administration (NASA), or commercial), are designed to ensure

low-risk, **high reliability end items. Low-quantity production rates** and **unique** designs minimize opportunities to take advantage of volume production and test practices. Technology development that **facilitates the reliable testing** of systems, **reduces system life cycle costs,** and **expedites** the turn-around time and delivery schedules of space systems will provide a **competitive advantage** in what is clearly a growing and **global market.**

The **increasing complexity** of microelectronics devices and the trend toward smaller, **more complex satellites** presents **technology challenges** in the test area related to time, cost, test capacity/capability, and metrology. **Needed improvements** include more effective means of measuring, controlling, and verifying manufacturing operations; improved **nondestructive test methods** and sensor techniques; sophisticated, high-quality **software engineering tools**; and the development of new or **improved metrology and dosimetry** capabilities.

Application of **photonics and fiber optics** is rapidly increasing, and this **raises numerous reliability and radiation hardness issues** related to testing and space application. Realistically and/or cost effectively testing under on-orbit environmental conditions and system applications is difficult or impossible with large space structures. This reality is forcing **increased use and reliance on dynamic modeling and prediction techniques. Finally,** test engineering and application of **design and test philosophies** targeted at **automated test and checkout**, built-in test (BIT), and increased application of knowledge-based, expert systems for data acquisition and analysis will be **key in achieving cost objectives while maintaining or improving reliability.**

Except for the **military weapons threat,** technologies related to space qualification and testing will have dual-use application for most space systems. As indicated earlier, the entire space community is **driven by economic factors** to build more **reliable systems in less time** and at **reduced costs. Development and application** of critical qualification and testing technologies **will play a major role** in accomplishing DoD, NASA, and commercial program **cost, performance, and schedule objectives.**

A related problem is that methodologies must be developed to produce and identify parts and materials in large quantities, with assured high reliability. The current specification system does not allow quality criteria to be used; therefore, parts and materials that meet existing specification requirements may not have the required reliability for space missions. The current practice for space equipment is to identify and control the

parts and materials at least to the manufacturing lot numbers. If assured-reliability parts and materials were developed and made available as standard items, considerable in-process space vehicle testing costs could be eliminated without reducing mission success probability.

# III. TECHNOLOGY SUMMARIES

The following section contains graphical presentations of the space-critical technologies with detailed physical parameters, recommended changes in export controls, and potential for CRDAs and International MOUs along with a series of comparative tables. The purpose of these tables is to give the reader an appreciation of the status of the identified space-critical technologies.

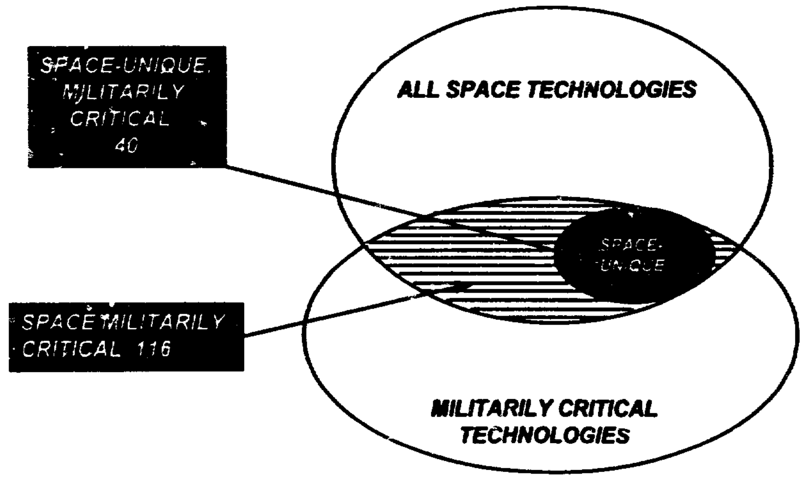
## A. TECHNOLOGY MATRIX SUMMARY

In this section, Table III-1 summarizes the number of space technologies recommended for decontrol, control, or liberalization.

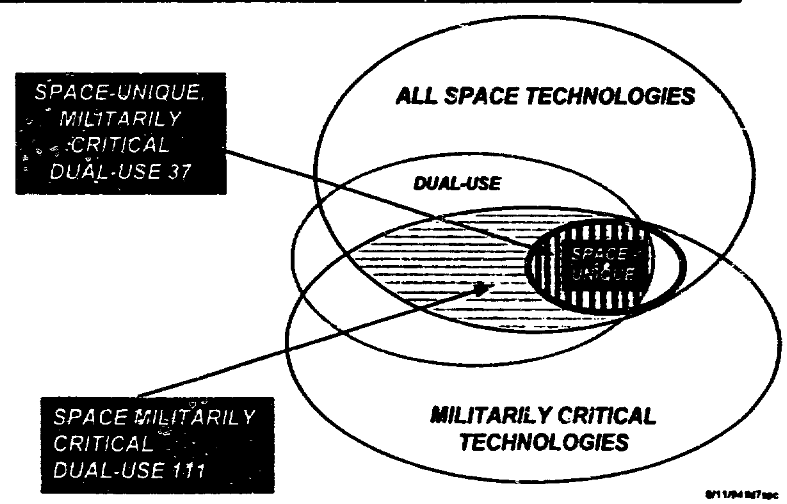
**Table III-1. SSTWG Critical Space Technology Summary**

| Tasks \ Subgroups | Totals | Space Systems Integ. | Launch Vehicles | Structures | Propulsion | Power and Thermal Mgt | Communications | Electronics and Computers | Astronautics | Sensors and Surveillance | Optics | Vulner. and Surviv. | Qualification and Testing |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Militarily** | | | | | | | | | | | | | |
| --Space-Critical | 116 | 9 | 3 | 25 | 22 | 12 | 7 | 13 | 4 | 6 | 7 | 6 | 2 |
| --Space-Critical Unique | 40 | 4 | 3 | 4 | 6 | 7 | 0 | 9 | 1 | 1 | 1 | 2 | 2 |
| **Dual-Use** | | | | | | | | | | | | | |
| --Space-Critical | 111 | 9 | 3 | 25 | 22 | 12 | 7 | 12 | 4 | 4 | 5 | 6 | 2 |
| --Space-Critical Unique | 37 | 4 | 2 | 4 | 6 | 7 | 0 | 8 | 1 | 0 | 1 | 2 | 2 |
| **Export Control** | | | | | | | | | | | | | |
| --Space-Critical | | | | | | | | | | | | | |
| - Decontrolled | 27 | 2 | 0 | 1 | 7 | 0 | 7 | 6 | 3 | 0 | 0 | 0 | 1 |
| - Liberalized | 31 | 0 | 0 | 13 | 1 | 2 | 0 | 3 | 0 | 5 | 6 | 1 | 0 |
| - Added | 3 | 0 | 0 | 1 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| --Space-Critical Unique | | | | | | | | | | | | | |
| - Decontrolled | 12 | 0 | 0 | 0 | 6 | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 1 |
| - Liberalized | 10 | 0 | 0 | 3 | 0 | 1 | 0 | 3 | 0 | 1 | 1 | 1 | 0 |
| - Added | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Needing Investment** | 36 | 3 | 2 | 5 | 6 | 7 | 0 | 9 | 0 | 1 | 1 | 0 | 2 |
| **Proposed** | | | | | | | | | | | | | |
| --CRDA | 30 | 4 | 2 | 3 | 4 | 7 | 0 | 6 | 1 | 0 | 1 | 0 | 2 |
| --MOU | 33 | 3 | 1 | 2 | 6 | 6 | 7 | 5 | 1 | 1 | 1 | 0 | 0 |

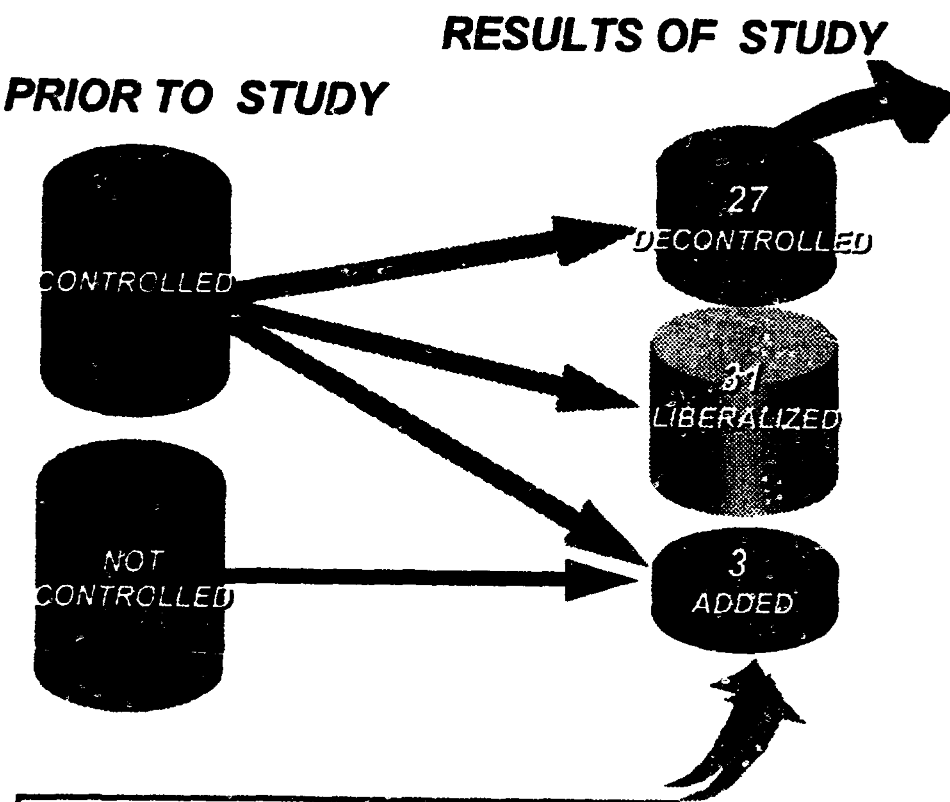
## RESULTS




## CRITICAL DUAL-USE SPACE TECHNOLOGIES



# RECOMMENDED EXPORT CONTROL CHANGES




Ring Lasers
Fiber Optic Gyros
Accelerometers
Adaptive Antennas
Integrated Phased Array Antennas
Multi-Beam Antennas
Antenna Side Lobe Control Reflectors
Antenna Side Lobe Control Phased Arrays
Space-Solid State Amplifiers
High-Data Rate Spread Spectrum Receivers
Rad Hard Archival Data Storage Systems
Rad Hard Electronics/computers
Rad Hard Nonvolatile Memory
Rad Hard Packaging
Rad Hard Optical-Domain Data Processing
Rad Hard Opto-electronic Integrated Circuits
Electric Propulsion Systems
Reusable $LO_2/LH_2$ Upper Stages
Reusable $LO_2/LH_2$ Booster
Reusable $LO_2$/RP-1 Booster
Expendable Hybrids
Thermal Vacuum Simulation
"Smart" Materials with Memory
Algorithms to Model Control Structure Interactions
Algorithms for Probabilistic Structural Analysis & Design
Mission Expert Systems
Standard Interfaces & Interconnections

Damage -Tolerant Organic Composite Primary Structures
Radiation-Resistant Insulators
Solar Photovoltaic Cells

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## B. MILITARILY CRITICAL SPACE TECHNOLOGIES

In this section, Tables III-2 through III-13 provide detailed information regarding all 116 militarily critical space technologies, including their critical physical parameters. The charts also indicate dual-use applicability and export control recommendations and suggest international partners for cooperative research.

Table III-2. Militarily Critical Space Technologies: Space Systems Integration

| Technology | Military Parameters | Space-Unique (Y or N) | Dual-Use (Y or N) | Export Control (Y or N) | Proposed CRDAs (Y or N) | Proposed Int'l MOUs (Y or N) | R&D Funding (I, W/O, or ADQ*) |
|---|---|---|---|---|---|---|---|
| Space Debris Cataloguing | Detect a 1-cm object at an altitude of 540 nm | Y | Y | N | Y | Russia, France, Japan, UK, China | ADQ |
| Payload Integration | See Table III-3 | | | | | | |
| Mission Operations | | | | | | | |
| --Standardization of Ground Control | Standard graphical user interfaces for all common operations < 1 hr retraining | Y | Y | N | Y | France, Russia, Japan | I |
| --Satellite Autonomy | Unattended operations for 30 days | Y | Y | N | Y | France, Russia, Japan | I |
| --On-Board Data Processing | 100:1 reduction in data stream | N | Y | N | Y | France, Russia, Japan | I |
| --Expert Systems | > Class 2 anomalies | N | Y | N (D) | Y | France, Russia, Japan | I |
| Standard | | | | | | | |
| --Interfaces and Interconnections (Mechanical and Electrical) | 3 standards or less | N | Y | N (D) | Y | Russia, France, China | I |
| --Buses | 3 standards or less | N | Y | N | Y | Russia, France | I |
| --Interfaces for Buses | Standard interface modular box with common connectors | N | Y | N | Y | Russia, France | I |
| High-Fidelity, Zero-Gravity Simulation | 6 degrees of freedom<br>< 0.1 percent simulation error for > 30 sec | Y | Y | N | Y | N | I |
| --Large Chamber Size | > 6 m x 4 m x 20 m | | | | | | |

(D) Dropped from control

* I = Inadequate Funding; W/O = Without Funding; ADQ = Adequate Funding

**Table III-3. Militarily Critical Space Technologies: Launch Vehicles**

| Technology | Military Parameters | Space-Unique (Y or N) | Dual-Use (Y or N) | Export Control (Y or N) | Proposed CRDAs (Y or N) | Proposed Int'l MOUs (Y or N) | R&D Funding (I, W/O, or ADQ*) |
|---|---|---|---|---|---|---|---|
| Launch Operations<br>--Automated Launch Processing: Model-based expert system for reactive control, fault detection, and processing | Launch-on-need within < 30 days | Y | Y | N | Y | Y | I |
| Aerothermodynamics<br>--Boundary Layer Transition<br>--Air Breathing Propulsion Design | Prediction model of Mach, altitude and thrust for > Mach 8 | Y | N | Y | Y | N | I |
| Computational Fluid Dynamics (CFD) Software Development | 50 percent reduction software personnel<br>1750 MIL-STD processor compatible | Y | Y | N | N | N | ADQ |
| Propulsion—see Launch section in Propulsion Table | | | | | | | |
| Structures—see Structures section in Structures Table | | | | | | | |

(D) Dropped from control

* I = Inadequate Funding; W/O = Without Funding; ADQ = Adequate Funding

Table III-4. Militarily Critical Space Technologies: Structures

| Technology | Military Parameters | Space-Unique (Y or N) | Dual-Use (Y or N) | Export Control (Y or N) | Proposed CRDAs (Y or N) | Proposed Int'l MOUs (Y or N) | R&D Funding (I, W/O, or ADQ*) |
|---|---|---|---|---|---|---|---|
| Long-term, Zero-g Cryogenic Storage and Acquisition Systems | High durability to meet criteria for 100 flights before major overhaul | Y | Y | Y (+) | Y | Russia | I |
| Space Environmental-Resistant Coatings | Resistance to degradation by atomic oxygen, UV, and cosmic radiation for 30 years space station lifetime; Operate > 7 yrs (see specific data in Vulnerability table) | Y | Y | Y (+) | Y | Russia | I |
| Multi-Use Panels for Satellites | Weight reduction of > 30 percent over equivalent metallic systems | Y | Y | N | N | N | I |
| Al-Li Materials | Machinability/weldability w/15 percent higher specific strength over Al 2219 | N | Y | Y (+) | N | N | I |
| Advanced C-C Composites | Lightweight panels, smooth surfaces, and nonintrusive, reusable fasteners | N | Y | Y (+) | Y | N | I |
| Titanium Matrix Composite Materials, Organic Composites | Retained strength at 1500 °F continuous operating temperature | N | Y | Y (+) | N | N | I |
| Ceramic Matrix Composite Materials | Retained strength at 2300 °F continuous operating temperature | N | Y | Y (+) | N | N | I |
| High-Temperature Organic Composites | 800 °F sustained operating temperature | N | Y | Y (+) | Y | N | I |
| Room-Temperature Curing Organic Composites | Curing at 100 °F with specific strength of autoclaved Gr-Ep/Gr-Pi | N | Y | Y (+) | N | N | I |
| "Smart" Materials With Memory | Ability to change shape within 10 ms | N | Y | N (D) | N | N | I |
| Adaptive Control Systems for Precision Lightweight and Flexible Structures | Distributed control systems: fuzzy logic self-organized controllers | N | Y | N | N | Russia | I |
| Near Net-Shape Forming of Metallic Structures | Significant reduction in current aerospace manufacturing with up to 50 percent less scrap | N | Y | Y (+) | Y | Germany | I |
| Damage-Tolerant Organic Composite Primary Structures | Noncatastrophic failure after impacts--no major delaminations | N | Y | Y (N) | Y | N | I |

(D) Dropped from control

(N) Needs to be added to controls

* I = Inadequate Funding; W/O = Without Funding; ADQ = Adequate Funding

(+) Increased critical threshold thus freeing up technologies below this parameter

Table III-4. Militarily Critical Space Technologies: Structures (Continued)

| Technology | Military Parameters | Space-Unique (Y or N) | Dual-Use (Y or N) | Export Control (Y or N) | Proposed CRDAs (Y or N) | Proposed Int'l MOUs (Y or N) | R&D Funding (I, W/O, or ADQ*) |
|---|---|---|---|---|---|---|---|
| Complex Geometry Organic Composites | 33 percent weight reduction over equivalent metallic structures with less complex manufacturing processes | N | Y | Y (+) | Y | Russia | I |
| Algorithms to Model Control-Structure Interactions for Flexible Structures | Complex vibrational models: nonlinear dynamics models | N | Y | N (D) | N | Russia | I |
| Algorithms for Probabilistic Structural Analysis and Design | Reliability prediction and control to reduce weight and cost | N | Y | N (D) | N | N | I |
| Launch Structures | | | | | | | I |
| --Thermal Protection System (TPS) Carbon-Carbon (C-C) | Oxidation-resistant $> 100$ flights $< 1.6$ lb/ft$^2$ 3000 °F max. continuous operating temp. | N | Y | Y (+) | Y | Germany, France | |
| --Reusable, Cryogenic Main Propellant Tank and Composite Feed Lines | High durability to meet criteria for 100 flights before major overhaul | Y | Y | Y (+) | Y | N | I |
| --TPS Radiant Shield | Oxidation-resistant $>100$ flights $< 1$ lb/ft$^2$, 350–1000 °C | N | Y | Y (+) | Y | Russia | I |
| --TPS Refractory Blanks | Oxidation-resistant $>100$ flights $< 1$ lb/ft$^2$, $< 600$ °C | N | Y | Y | Y | Y | I |
| --High-Temperature Seals | High durability to meet criteria for 100 flights before major overhaul 3000 °F continuous operating temp. | N | Y | Y | Y | Russia | I |
| --Lightweight Metallic Structure | 15 percent < weight of Al 2219 with similar properties with 100 percent strength and stiffness of Al 2219 | N | Y | Y | Y | Russia | I |
| --Titanium Metal Matrix Composite Structures | Strength and stiffness retained at 1500 °F | N | Y | N | N | N | I |
| --Ceramic Matrix Composite | Strength and stiffness retained at 2400 °F | N | Y | N | N | N | I |
| --Room-Temperature Curing Organic Composites | Curing < 100 °F with specific strength of autoclaved Gr-Ep/Gr-Pi | N | Y | N | N | N | I |

(D) Dropped from control

(N) Needs to be added to controls

* I = Inadequate Funding; W/O = Without Funding; ADQ = Adequate Funding

(+) *Increased critical threshold thus freeing up technologies below this parameter*

Table III-5. Militarily Critical Space Technologies: Propulsion

| Technology | Military Parameters | Space-Unique (Y or N) | Dual-Use (Y or N) | Export Control (Y or N) | Proposed CRDAs (Y or N) | Proposed Int'l MOUs (Y or N) | R&D Funding (I, W/O, or ADQ*) |
|---|---|---|---|---|---|---|---|
| Elecric Propulsion Systems | Low power 1.5 to10 kWe<br>High power > 10 kWe | Y | Y | N<br>(D) | N | Italy, Russia, Germany | I |
| Liquid Rocket Propulsion Systems | I(t) > 1.1 MN<br>F(vac) > 220 kN | N | Y | Y<br>(+) | N | Russia | I |
| Cryogenic Propellant Storage and Refrigeration | Loss rate < 30 percent/yr<br>Temperature < 100 K | N | Y | Y | N | N | I |
| High-Pressure Turbopumps | Exit pressure > 17.5 MPa | N | Y | Y | N | N | I |
| High-Pressure Thrust Chambers | P(c) > 10.6 MPa | N | Y | Y | N | N | I |
| Micro-Orifice Injectors for Small Engines | Orifice < 0.30 mm<br>F(vac) < 18 kN | N | Y | Y | N | N | I |
| One-Piece C-C Thrust Chambers | Density > 1.4 gm/cc<br>Tensile strength > 28.4 MPa | N | Y | Y | N | France | I |
| Pulsed Liquid Rocket Engines | F/W > 100:1<br>Response Time < 0.030 sec | N | Y | Y | N | N | I |
| Solid Rocket Propulsion Systems | I(t) > 1.1 MN F(vac) > 220 kN<br>I[sp (vac)] > 2.4 kN/kg<br>Stage mass fraction > 88 percent<br>Prop solids loading > 86 percent | N | Y | Y | N | N | I |
| Propellant Bonding Systems | Bond strength > Propellant strength | N | Y | Y | N | Germany | I |
| Composite Motor Cases | Diameter > 0.61 m<br>PV/W > 2.54 E+6 cm | N | Y | Y | N | N | I |
| Thrust Vector Control Systems | Total angular velocity > ± 5 degrees<br>Angular velocity > 20 deg/sec<br>Angular accel. > 40 deg/sec$^2$ | N | Y | Y | N | N | I |
| Nozzles | Thrust > 45 kN<br>Max. erosion rate < 0.075 km/sec | N | Y | Y | N | France | I |
| High-Energy Propellant Ingredients | I[sp(vac)] > 2.4 kN/kg | N | Y | Y | N | N | I |
| Hybrid Rocket Propulsion Systems | I(total) > 1.1 MN<br>F(vac) > 220 kN | N | Y | Y | Y | Japan | I |

(D) Dropped from control

(N) Needs to be added to controls

* I = Inadequate Funding; W/O = Without Funding; ADQ = Adequate Funding

(+) Increased critical threshold thus freeing up technologies below this parameter

**Table III-5. Militarily Critical Space Technologies: Propulsion (Continued)**

| Technology | Military Parameters | Space-Unique (Y or N) | Dual-Use (Y or N) | Export Control (Y or N) | Proposed CRDAs (Y or N) | Proposed Int'l MOUs (Y or N) | R&D Funding (I, W/O, or ADQ*) |
|---|---|---|---|---|---|---|---|
| Nuclear Propulsion Systems | F/W >20:1<br>Mean outlet temp. > 2800 K<br>Start-up time to 1800 K < 60 sec | N | Y | Y | N | N | W/O |
| Launch Vehicle Propulsion | | | | | | | |
| --Reusable $LO_2/LH_2$ Propulsion | 50 reuses without refurbishment<br>0.9995 reliability I(sp) > 450<br>250 klb thrust | Y | Y | N<br>(D) | Y | Russia | I |
| --Tripropellants | 50 reuses without refurbishment<br>0.9995 reliability I(sp) > 450<br>250 klb thrust | Y | Y | N<br>(D) | N | Russia | I |
| --Expendable<br>- $LO_2/LH_2$ Upper Stages | < 2 times current system cost<br>550 ± klb s.l. thrust<br>450 sec I[sp(vac)] | Y | Y | N<br>(D) | Y | Russia | I |
| - $LO_2/LH_2$ Booster | < 2 times current system cost<br>550 klb s.l. thrust<br>380 sec I[sp(vac)] | Y | Y | N<br>(D) | Y | Russia | I |
| - $LO_2$/RP-1 Booster | < 2 times current system cost<br>300 klb s.l. thrust<br>275 sec I[sp(vac)] | Y | Y | N<br>(D) | Y | Russia, China | I |
| - Hybrids | Price equal to monolithic solids<br>> 400 klb thrust<br>275 sec I[sp(vac)] | N | Y | N<br>(D) | Y | N | I |

(D) Dropped from control

(N) Needs to be added to controls

* I = Inadequate Funding; W/O = Without Funding; ADQ = Adequate Funding

(+) Increased critical threshold thus freeing up technologies below this parameter

**Table III-6. Militarily Critical Space Technologies: Power and Thermal Management**

| Technology | Military Parameters | Space-Unique (Y or N) | Dual-Use (Y or N) | Export Control (Y or N) | Proposed CRDAs (Y or N) | Proposed Int'l MOUs (Y or N) | R&D Funding (I, W/O, or ADQ*) |
|---|---|---|---|---|---|---|---|
| Solar—Photovoltaic | Production technology: Specific power > 300 W/m$^2$ Beginning of life (BOL) at 28 °C at cell level | Y | Y** | Y (N) | Y | N | I |
| Solar—Dynamic | Production technology: System-specific power > 25 W/kg | Y | Y** | Y | Y | Russia | I |
| --Materials | All refractory heat engine components at temperatures > 1250 K | Y | Y** | Y | Y | Russia | I |
| --Software | All analysis of all transient heat engine cycle performance | Y | Y** | Y | Y | Russia | I |
| Nuclear Radioisotope | | | | | | | |
| --Materials | Plutonium 238 > 1 gram Neptunium 237 > 1 gram | N | Y** | Y | N | Russia | I |
| Nuclear Fission | | | | | | | |
| --Materials | High-purity refractory metals at > 1250 K High-temp. thermoelectric materials > 1000 K Highly enriched uranium > 20 percent U-235 | N | Y | Y (+) | N | Russia | I |
| --Components | Radiation-resistant electrical insulators > 1.0 E+18 nvt† | N | Y | (N) | N | N | I |

(D) Dropped from control

(N) Needs to be added to controls

* I = Inadequate Funding; W/O = Without Funding; ADQ = Adequate Funding

(+) Increased critical threshold thus freeing up technologies below this parameter

** With relaxed specifications

† nvt = neutron velocity time

**Table III-6. Militarily Critical Space Technologies: Power and Thermal Management (Continued)**

| Technology | Military Parameters | Space-Unique (Y or N) | Dual-Use (Y or N) | Export Control (Y or N) | Proposed CRDAs (Y or N) | Proposed Int'l MOUs (Y or N) | R&D Funding (I, W/O, or ADQ*) |
|---|---|---|---|---|---|---|---|
| Long-life Cryogenic Coolers | Temp: / Efficiency (W/W)†<br>(1) 120–180 K < 10<br>(2) 60–80 K < 75<br>(3) 30–40 K < 200<br>(4) 9–11 K < 750<br>Vibration: < 0.02 N rms<br>Unattended life: 7 years<br>Cooling loads:<br>(1) 120–180 K < 10 W<br>(2) 60–80 K < 5 W<br>(3) 30–40 K <1 W<br>(4) 9–11 K < 0.5 W | Y | Y** | Y (+) | Y | UK | I |
| Spacecraft Thermal Control | | | | | | | |
| --Liquid Metal Heat-Pipes | > 600 K | N | Y** | N | N | Russia | I |
| --Advanced Radiators (Composite) | < 30 kg/kW<br>< 7 $m^2$/kW | Y | Y** | N | Y | France | I |
| --High-Power Density Electronics Cooling | > 1000 W/$cm^2$ | N | Y** | N | Y | N | I |
| Energy Storage—Batteries | Components with an energy density of:<br>100 W-hr/kg > 1000 cycles<br>75 W-hr/kg > 25,000 cycles<br>> 250 W-hr/kg (primary battery) | Y | Y | N | Y | Canada | I |

(D) Dropped from control

(N) Needs to be added to controls

† Watts input power per Watt of cooling

* I = Inadequate Funding; W/O = Without Funding; ADQ = Adequate Funding

(+) Increased critical threshold thus freeing up technologies below this parameter

** With relaxed specifications

**Table III-7. Militarily Critical Space Technologies: Communications**

| Technology | Military Parameters | Space-Unique (Y or N) | Dual-Use (Y or N) | Export Control (Y or N) | Proposed CRDAs (Y or N) | Proposed Int'l MOUs (Y or N) | R&D Funding (I, W/O, or ADQ*) |
|---|---|---|---|---|---|---|---|
| Antennas | | | | | | | |
| --Adaptive | Null depth > 25 db, adaptation time < 10 msec | N | Y | N (D) | N | Y** | ADQ |
| --Integrated Phased Array | Number of radiating elements > 1000 | N | Y | N (D) | N | Y** | ADQ |
| --Multi-Beam Antennas | Spatial resolution single beam < 0.5 degrees | N | Y | N (D) | N | Y** | ADQ |
| --Side Lobe Control | | | | | | | |
| - Reflectors | Side lobe > 35 db at aspect angles > 5 degrees | N | Y | N (D) | N | Y** | ADQ |
| - Phased Arrays | Side lobe > 50 db below the mean peak | N | Y | N (D) | N | Y** | ADQ |
| Space Solid-State Amplifiers | 250 MHz > 25 W<br>8 GHz > 2 W<br>20 GHz > 3 W<br>60 GHz > 1/4 W<br>10 yr, 30-percent efficiency | N | Y | N (D) | N | Y** | ADQ |
| Receiver | | | | | | | |
| --High Data Rate<br>--Spread Spectrum | > 1 Gb per second | N | Y | N (D) | N | Y** | ADQ |

(D) Dropped from export control

* I = Inadequate Funding; W/O = Without Funding; ADQ = Adequate Funding

** MILSATCOM program currently has international study looking at joint development of MOUs for communications satellites with Canada, UK, and France.

**Table III-8. Militarily Critical Space Technologies: Electronics and Computers**

| Technology | Military Parameters | Space-Unique (Y or N) | Dual-Use (Y or N) | Export Control (Y or N) | Proposed CRDAs (Y or N) | Proposed Int'l MOUs (Y or N) | R&D Funding (I, W/O, or ADQ*) |
|---|---|---|---|---|---|---|---|
| Architecture | | | | | | | |
| --Digital Signal Processors | Rad hard > 1 Mrad<br>Throughput > 1 MOPs<br>Reprogrammable | Y | Y** | Y<br>(+) | N | N | I |
| --High-Speed Data Buses | Rad hard > 1 Mrad and<br>Throughput > 1 MOPs | Y | Y** | N | N | N | I |
| Rad Hard Electronics Technology | | | | | | | |
| --Archival Data Storage Systems | Rad hard > 1 Mrad<br>Capacity > 10 GB<br>Continuous operation > 10 years | Y | Y** | N<br>(D) | Y | France,<br>Japan | I |
| --Electronics/Computers | Rad hard > 1 Mrad<br>Low-cost product line | Y | Y | N<br>(D) | Y | France | I |
| --Cryogenic Electronics | Rad hard > 500 krad | Y | N | Y<br>(+) | Y | N | I |
| --Field Programmable Devices | Rad hard > 500 krad<br>Density > 5 k gates | Y | Y** | Y<br>(+) | Y | France,<br>Japan | W/O |
| --Nonvolatile Memory | Rad hard > 1 Mrad<br>Retention > 10 years<br>Endurance > 1.0 E+12 cycles | Y | Y | N<br>(D) | Y | France | I |
| --Packaging | Rad hard > 10 Mrad<br>Hermetic seal<br>Density improvement > 10 X | N | Y** | N<br>(D) | Y | France, Japan,<br>Germany,<br>Ukraine | I |
| --Neural Networks | Rad hard > 1 Mrad<br>2–3000 connections | N | Y | Y | Y | Finland | I |
| --Dielectrically Isolated Materials (SCI) | Film thickness < 0.3 μm<br>Uniformity > 95 percent<br>Cost < $20/wafer<br>Defects < 10/cm$^2$ | N | Y** | N | Y | France | I |

(D) Dropped from export control

* I = Inadequate Funding; W/O = Without Funding; ADQ = Adequate Funding

(+) Increased critical threshold thus freeing up technologies below this parameter for export

** The dual-use requirements are less than the military requirements.

**Table III-8. Militarily Critical Space Technologies: Electronics and Computers (Continued)**

| Technology | Military Parameters | Space-Unique (Y or N) | Dual-Use (Y or N) | Export Control (Y or N) | Proposed CRDAs (Y or N) | Proposed Int'l MOUs (Y or N) | R&D Funding (I, W/O, or ADQ*) |
|---|---|---|---|---|---|---|---|
| Computer Technology | | | | | | | |
| --Software | Fault-tolerant<br>On-orbit reprogrammability | N | Y** | N | Y | N | I |
| --Optical Domain Data Processing | Rad hard > 500 krad | Y | Y** | N (D) | Y | N | I |
| --Opto-Electronic Integrated Circuits | Rad hard > 500 krad | Y | Y | N (D) | N | France | I |

(D) Dropped from export control

* I = Inadequate Funding; W/O = Without Funding; ADQ = Adequate Funding

(+) Increased critical threshold thus freeing up technologies below this parameter for export

** The dual-use requirements are less than the military requirements.

**Table III-9. Militarily Critical Space Technologies: Astronautics**

| Technology | Military Parameters | Space-Unique (Y or N) | Dual-Use (Y or N) | Export Control (Y or N) | Proposed CRDAs (Y or N) | Proposed Int'l MOUs (Y or N) | R&D Funding (I, W/O, or ADQ*) |
|---|---|---|---|---|---|---|---|
| Ring Laser | Bias < 0.003 degree drift rate/hr<br>Random walk 0.0015 degree/√hr<br>Scale factor < 5 ppm<br>Colored noise < 0.003 degree/hr<br>Misalignment 1.5 arc sec | N | Y | N (D) | N | N | ADQ |
| Fiber Optic Gyro | Bias < 0.1 degree drift rate/hr<br>Random walk 0.08 degree/√hr<br>Scale factor < 100 ppm<br>Colored noise < 0.035 degree/hr<br>Misalignment 20 arc sec | N | Y | N (D) | N | N | ADQ |
| Accelerometers | Bias < 25 μg<br>White noise < 10 μg/√hz<br>Scale factor < 120 ppm<br>Colored noise < 15 μg<br>Misalignment 0.2 arc sec | N | Y | N (D) | N | N | ADQ |
| GPS-Aided Navigation | Subsystem Rel > 0.9999<br>Vib > 50 gs<br>SEU Resilient<br>Latch-up free<br>Position error:<br>X = 0.3, Y = 0.3,<br>Z = 0.3 m at 3 gs for 3 axis | Y | Y | Y | Y | Y | ADQ |

(D) Dropped from export control

* I = Inadequate Funding; W/O = Without Funding; ADQ = Adequate Funding

**Table III-10. Militarily Critical Space Technologies: Sensors and Surveillance**

| Technology | Military Parameters | Space-Unique (Y or N) | Dual-Use (Y or N) | Export Control (Y or N) | Proposed CRDAs (Y or N) | Proposed Int'l MOUs (Y or N) | R&D Funding (I, W/O, or ADQ*) |
|---|---|---|---|---|---|---|---|
| Diode Laser Beacons | > 10 W | Y | N | Y (+) | N | France | I |
| Diode Laser Optical Communications | Data rate > 1 Gb/sec | N | Y | Y (+) | N | France | I |
| High-Resolution Charged Coupled Arrays | Spatial resolution: Pitch of < 25 µm, > 1.0 E+3 pixel elements | N | Y | Y (+) | N | France | ADQ |
| IR Detector Array Sensor | 1 or more space-qualified elements | N | Y | Y (+) | N | France | I (for far IR) |
| SAR Space-Based | < 3 m resolution at > 200 km | N | Y | Y (+) | N | Canada, France, Russia | I |
| Pattern Recognition Radar Algorithms | All ultra wideband single expansion mode pulse (SEMP) measurement algorithms | N | N | Y | N | UK | I |

(D) Dropped from export control

* I = Inadequate Funding; W/O = Without Funding; ADQ = Adequate Funding

(+) Increased critical threshold thus freeing up technologies below this parameter for export

**Table III-11. Militarily Critical Space Technologies: Optics**

| Technology | Military Parameters | Space-Unique (Y or N) | Dual-Use (Y or N) | Export Control (Y or N) | Proposed CRDAs (Y or N) | Proposed Int'l MOUs (Y or N) | R&D Funding (I, W/O, or ADQ*) |
|---|---|---|---|---|---|---|---|
| Directed Energy Optics | < 1.0 E–3 absorption<br>> 1.0 E+4 W/cm$^2$ incident radiation | N | N | Y (+) | N | Y | I |
| Lightweight Space Qualified Optics | < 20 percent bulk weight<br>30 kg/m$^2$ areal density<br>Total weight > 10 kg<br>> 1 m aperture | Y | Y | Y (+) | Y | Y | I |
| Passively and Actively Cooled Optics | > 1.0 E+4 W/cm$^2$<br>Incident radiation for 30 sec | N | Y | Y (+) | Y | Y | I |
| Adaptive Optics | > 10 cm aperture<br>> 100 Hz bandwidth<br>< 1/2 λ flatness for > 100 Hz bandwidth<br>λ = 0.5 μm | N | Y | Y (+) | Y | Y | I |
| Silicon Optics | Single crystal substrate w/optical coating<br>< 200 ppm absorption total (substrate and coating)<br>> 25 cm aperture<br>< 200 ppm optical scatter | N | N | Y (+) | N | N | I |
| Optical Coatings | Scatter < 3.0 E–3 and absorption < 1.0 E–3 (for surface > 30-cm diameter) | N | Y | Y (+) | Y | Y | I |
| Segmented Optics | > 1 m aperture equivalent | N | Y | Y | Y | N | I |

(D) Dropped from export control

* I = Inadequate Funding; W/O = Without Funding; ADQ = Adequate Funding

(+) Increased critical threshold thus freeing up technologies below this parameter for export

**Table III-12. Militarily Critical Space Technologies: Vulnerability and Survivability**

| Technology | Military Parameters | Space-Unique (Y or N) | Dual-Use (Y or N) | Export Control (Y or N) | Proposed CRDAs (Y or N) | Proposed Int'l MOUs (Y or N) | R&D Funding (I, W/O, or ADQ*) |
|---|---|---|---|---|---|---|---|
| Nuclear/Natural Radiation Hardening | Total dose > 5.0 E+5 rads(Si)<br>Dose rate > 5.0 E+8 rads(Si)/sec<br>SEU < 1.0 E–7 errors/bit/day<br>Newton fluence > 1.0 E+10 n/cm$^2$ | N | Y | Y | N | N | ADQ |
| Electromagnetic Pulse | Field strength > 30 kV/m | N | Y | Y | N | N | ADQ |
| High-Power RF Filters for Sensor Optics | > 40 db attenuation of RF energy and > 96 percent transmission of sensor frequency | Y | Y | Y (+) | N | N | ADQ |
| Signature Identification for Space Objects | Codes and algorithms with range of frequency from vacuum UV (0.11 μ) through LWIR (25 μ) | Y | Y | Y | N | N | ADQ |
| Laser Effects | Energy density > 1.0 E–3 joule/cm$^2$ with dwell times > 1 μsec | N | Y | Y | N | N | ADQ |

(D) Dropped from export control

* I = Inadequate Funding; W/O = Without Funding; ADQ = Adequate Funding

(+) Increased critical threshold thus freeing up technologies below this parameter for export

**Table III-13. Militarily Critical Space Technologies: Qualification and Testing**

| Technology | Military Parameters | Space-Unique (Y or N) | Dual-Use (Y or N) | Export Control (Y or N) | Proposed CRDAs (Y or N) | Proposed Int'l MOUs (Y or N) | R&D Funding (I, W/O, or ADQ*) |
|---|---|---|---|---|---|---|---|
| Thermal Vacuum Simulation | 1.0 E–8 Torr<br>–320 to +250 °C | Y | Y | N<br>(D) | Y | N | I |
| Space Environmental Simulator | 1.0 E–5 Torr | Y | Y | N | Y | N | I |
| --Atomic Oxygen | Energy 5 eV<br>Flux 1.0 E+14/cm$^2$ | | | | | | |
| --Electrons | Energy 500 eV<br>Flux 1.0 E+12/cm$^2$/MeV | | | | | | |
| --Protons | Energy 1 MeV<br>Flux 1.0 E+7/cm$^2$/MeV | | | | | | |
| --UV Radiation | 100 nm to 400 nm (1 sun equivalent) | | | | | | |
| --Temperature | –130 to 100 °C | | | | | | |
| --Hypervelocity Debris | Size 0.1 mm–1.0 mm<br>Flux 1.0 E–2 to 1.0 E+21 hits/hr/m$^2$<br>Velocity ~ 10 km/sec | | | | | | |

(D) Dropped from export control

* I = Inadequate Funding; W/O = Without Funding; ADQ = Adequate Funding

## C. TECHNOLOGY CAPABILITIES

In this section, Tables III-14 through III-23 provide a summary of the status of critical space technologies. Columns show the current capabilities of the technology when produced in the laboratory and when produced by industry—both for commercial and military applications.

**Table III-14. Technology Capabilities: Launch Vehicles**

| Technology | Military Parameters | Current Laboratory Capabilities | Current Industry Production Capabilities |
|---|---|---|---|
| Launch Operations<br>--Automated Launch Processing: Model-based expert system for reactive control, fault detection, and processing | Launch-on-need within < 30 days | Launch-on-need 7 days (laboratory demo portions) | Launch-on-need 24–60 days |
| Aerothermodynamics<br>--Boundary Layer Transition<br>--Air Breathing Propulsion Design | Prediction model of Mach<br>Altitude and thrust for > Mach 8 | Experimental nonvalidated CFD codes | None—Empirical data only |
| Computational Fluid Dynamics (CFD) Software Development | 50 percent reduction software personnel<br>1750 MIL-STD processor compatible | 50 percent reduction software personnel<br>1750 MIL-STD processor compatible | Working toward 50 percent reduction software personnel<br>1750 MIL-STD processor compatible |
| Propulsion—see Launch section in Propulsion table | | | |
| Structures—see Structures section in Structures table | | | |

Table III-15. Technology Capabilities: Structures

| Technology | Military Parameters | Current Laboratory Capabilities | Current Industry Production Capabilities |
|---|---|---|---|
| Long-term, Zero-g Cryogenic Storage and Acquisition Systems | High durability to meet criteria for 100 flights before major overhaul | Proof-of-concept test article built but never tested | None |
| Space Environmental-Resistant Coatings | Resistance to degradation by atomic oxygen, UV and cosmic radiation for 30 years space station lifetime; Operate > 7 yrs (see specific data on Vulnerability table) | 30-yr accelerated exposure to singular flux with no synergistic effects | Long-Duration Exposure Facility (LDEF) satellite with 5-yr 9-month lifetime |
| Multi-Use Panels for Satellites | Weight reduction of > 30 percent over equivalent metallic systems | Small parts built and tested | None |
| Al-Li Materials | Machinability/weldability w/15 percent higher specific strength over Al 2219 | 10 percent higher specific strength over Al 2219 with fatigue problems | None |
| Advanced C-C Composites | Lightweight panels, smooth surfaces and nonintrusive, reusable fasteners | Subscale panels built and tested | None |
| Titanium Matrix Composite Materials, Organic Composites | Retained strength at 1500 °F *continuous operating temperature* | Retained strength at 1200 °F *continuous operating temperature* without oxidizing | None |
| Ceramic Matrix Composite Materials | Retained strength at 2300 °F continuous operating temperature | Retained strength at 2000–2300 °F continuous operating temperature | Retained strength at 2000 °F continuous operating temperature |
| High-Temperature Organic Composites | 800 °F sustained operating temperature | 700 °F sustained operating temperature | 650 °F sustained operating temperature |
| Room-Temperature Curing Organic Composites | Curing at 100 °F with specific strength of autoclaved Gr-Ep/Gr-Pi | Curing at 100 °F with 10–20 percent less strength than that of autoclaved Gr-Ep/Gr-Pi | None |
| "Smart" Materials With Memory | Ability to change shape within 10 ms | Release mechanisms tested in lab | None |
| Adaptive Control Systems for Precision Lightweight and Flexible Structures | Distributed control systems: fuzzy logic self-organized controllers | Fuzzy controller on small beam | None |
| *Near Net-Shape Forming of Metallic* Structures | *Significant reduction in current aero-*space manufacturing with up to 50 percent less *scrap* | *Order-of-magnitude reductions in* NC-CAD/CAM part layups | *Reductions in scrap of up to* 50 percent demonstrated for sheet metal parts |
| Damage-Tolerant Organic Composite Primary Structures | Noncatastrophic failure after impacts No major delaminations | Damage-tolerant woven composite under development, only small test coupons | None |

**Table III-15. Technology Capabilities: Structures (Continued)**

| Technology | Military Parameters | Current Laboratory Capabilities | Current Industry Production Capabilities |
|---|---|---|---|
| Complex Geometry Organic Composites | 33 percent weight reduction over equivalent metallic structures with less complex manufacturing processes | Reduction of < 30 percent weight with same complexity of manufacturing | Reduction of 15 percent weight with same complexity of manufacturing |
| Algorithms to Model Control-Structure Interactions for Flexible Structures | Complex vibrational models: nonlinear dynamics models | Same as militarily critical<br>Demonstrated in lab | Limited applications in industry |
| Algorithms for Probabilistic Structural Analysis and Design | Reliability prediction and control in order to reduce weight and cost | Same as militarily critical<br>Available with some development | Limited applications in industry |
| Launch Structures | | | |
| --Thermal Protection System (TPS) Carbon-Carbon (C-C) | Oxidation Resistant<br>> 100 flights < 1.6 lb/ft$^2$<br>3000 °F max. continuous operating temp. | 100-flight reuse not tested; = 2.5 lb/ft$^2$ areal density) with coatings and fasteners; 3000 °F max. temperature | Limited applications in industry |
| --Reusable, Cryogenic Main Propellant Tank and Composite Feed Lines | High durability to meet criteria for 100 flights before major overhaul | Subscale, nonflight weight test articles built with limited tests accomplished | Tank not flight tested. Shuttle orbiter has reusable, noncomposite cryogenic feed lines |
| --TPS Radiant Shield | Oxidation-resistant<br>> 100 flights < 1 lb/ft$^2$, 350–1000 °C | Oxidation-resistant<br>> 100 flights < 1 lb/ft$^2$, 350–1000°C | Oxidation-resistant<br>> 100 flights < 1 lb/ft$^2$, 350–1000°C |
| --TPS Refractory Blanks | Oxidation-resistant<br>> 100 flights < 1 lb/ft$^2$, < 600 °C | Oxidation-resistant<br>> 100 flights < 1 lb/ft$^2$, < 600 °C | Oxidation-resistant<br>> 100 flights < 1 lb/ft$^2$, < 600 °C |
| --High-Temperature Seals | High durability to meet criteria for 100 flights before major overhaul.<br>3000 °F continuous operating temp. | 100-flight reuse not tested<br>Tested to 3000 °F max. temperature | Replacement/refurbishment after each flight (Shuttle)<br>Flown to 2300 °F max. temperature |
| --Lightweight Metallic Structure | 15 percent < weight of Al 2219 with similar properties with 100 percent strength and stiffness of Al 2219 | 15 percent < weight of Al 2219 with 100 percent strength and stiffness of Al 2219<br>10 percent < weight of Al 2219 but with fatigue problems | None |
| --Titanium Metal Matrix Composite Structures | Strength and stiffness retained at 1500 °F | Strength and stiffness retained at 1500 °F continuous operating temperature without oxidizing | None |
| --Ceramic Matrix Composite | Strength and stiffness retained at 2400 °F | Strength and stiffness retained at < 2300 °F, continuous operating temperature | Strength and stiffness retained at 2000 °F continuous operating temperature |
| --Room-Temperature Curing Organic Composites | Curing < 100 °F with specific strength of autoclaved Gr-Ep/Gr-Pi | Curing < 100 °F with 10 to 20 percent less specific strength than autoclaved Gr-Ed/Gr-iPi | None |

## Table III-16. Technology Capabilities: Propulsion

| Technology | Military Parameters | Current Laboratory Capabilities | Current Industry Production Capabilities |
|---|---|---|---|
| Elecric Propulsion Systems | Low power 1.5 to10 kWe<br>High power > 10 kWe | Low power 1.5 to10 kWe<br>High power > 10 kWe | Low power 1.5 to10 kWe<br>High power > 10 kWe |
| Liquid Rocket Propulsion Systems | I(t) > 1.1 MN<br>F(vac) > 220 kN | I(t) > 3200 MN<br>F(vac) up to 6.9 MN | I(total) up to 3200 MN<br>F(vac) up to 6.9 MN |
| Cryogenic Propellant Storage and Refrigeration | Loss rate < 30 percent/yr<br>Temperature < 100 K | Loss rate = 2–10 percent/yr<br>Temperature < 100 K | Loss rate = 2–10 percent/yr<br>Temperature < 100 K |
| High-Pressure Turbopumps | Exit pressure > 17.5 MPa | Exit pressure up to 21.2 MPa | Exit pressure up to 21.2 MPa |
| High-Pressure Thrust Chambers | P(c) > 10.6 MPa | P(c) up to 2–20 MPa | P(c) up to 20.0 MPa |
| Micro-Orifice Injectors for Small Engines | Orifice < 0.30 mm<br>F(vac) < 18 kN | Orifice sizes down to 0.15 mm<br>F(vac) = 5 N to 18 kN | Orifice sizes down to 0.15 mm<br>F(vac) = 5 N to 18 kN |
| One-Piece C-C Thrust Chambers | Density > 1.4 gm/cc<br>Tensile strength > 28.4 MPa | Density = 1.4–1.9 gm/cc<br>Tensile Strength 50 MPa+ | Density = 1.4–1.9 gm/cc<br>Tensile strength 50 MPa+ |
| Pulsed Liquid Rocket Engines | F/W > 100:1<br>Response time < 0.030 sec | F/W = 1000:1<br>Response time = 0.005 sec | F/W = 1000:1<br>Response time = 0.005 sec |
| Solid Rocket Propulsion Systems | I(t) > 1.1 MN F(vac) > 220 kN<br>I[sp (vac)] > 2.4 kN/kg<br>Stage mass fraction > 88 percent<br>Prop solids loading > 86 percent | I(total) = 2636 MN<br>I[s(vac)] = 3.2 kN/kg<br>F(vac) = 23 MN<br>Mass fraction = 88–93 percent<br>Solid loading = 86–92 percent | I(total) = 2636 MN<br>I[s(vac)] = 3.2 kN/kg<br>F(vac) = 23 MN<br>Mass fraction = 88–93 percent<br>Solid loading = 86–92 percent |
| Propellant Bonding Systems | Bond strength > Propellant strength | Bond strength > Propellant strength | Bond strength > Propellant strength |
| Composite Motor Cases | Diameter > 0.61 m<br>PV/W > 2.54 E+6 cm | Diameter < 4 m<br>PV/W 5.0 E+6 cm | Diameter < 4 m<br>PV/W 4.0 E+6 cm |
| Thrust Vector Control Systems | Total angular velocity > ± 5 degrees<br>Angular velocity > 20 deg/sec<br>Angular accel. > 40 deg/sec$^2$ | Total angular velocity = 2–15 degrees<br>Angular velocity = < 40 deg/sec<br>Angular accel. = < 50 deg/sec$^2$ | Total angular velocity = 2–15 degrees<br>Angular velocity < 40 deg/sec<br>Angular accel. = 50 deg/sec$^2$ |
| Nozzles | Thrust > 45 kN<br>Max. erosion rate < 0.075 km/sec | Thrust = up to 23 E+6 N<br>Erosion rates = 0.0 to 0.15 mm/sec | Thrust = up to 23 E+6 N<br>Erosion rates = 0.0 to 0.15 mm/sec |
| High-Energy Propellant Ingredients | I[sp(vac)] > 2.4 kN/kg | I[sp(vac)] = 2.5–3.2 kN/kg | I[sp(vac)] = 2.5–3.2 kN/kg |
| Hybrid Rocket Propulsion Systems | I(total) > 1.1 MN<br>F(vac) > 220 kN | Up to 18.4 MN<br>Up to 1.1 MN | Up to 18.4 MN<br>Up to 1.1 MN |

**Table III-16. Technology Capabilities: Propulsion (Continued)**

| Technology | Military Parameters | Current Laboratory Capabilities | Current Industry Production Capabilities |
|---|---|---|---|
| Nuclear Propulsion Systems | F/W >20:1<br>Mean outlet temp. > 2800 K<br>Start-up time to 1800 K < 60 sec | F/W goal of 40:1<br>Temp goal of 3000 K<br>Time goal of 1–10 sec | F/W goal of 4.0:1*<br>Temp goal of 2000 K*<br>5–10 minutes* |
| Launch Vehicle Propulsion | | | |
| --Reusable $LO_2/LH_2$ Propulsion | 50 reuses without refurbishment<br>0.9935 reliability I(sp) > 450<br>250 klb thrust | RL10A-5, multiple restart<br>16.5 klb thrust<br>360 sec I(sp) (s.l.)<br>445 sec I[sp(vac)] | I(sp) > 470 vac, 4 reuse SSME w/refurbishment<br>375 klb thrust (s.l.);<br>470 klb thrust (vac)<br>455 sec I[sp(vac)] |
| --Tripropellants | 50 reuses without refurbishment<br>0.9995 reliability I(sp) > 450<br>250 klb thrust | RD-701 (Russia) Capability<br>400 klb thrust (s.l.)<br>410 sec I(sp) (s.l.) | RD-701 (FSU) capability<br>400 klb thrust (S.l.)<br>410 sec I(sp) (s.l.) |
| --Expendable<br>- $LO_2/LH_2$ Upper Stages | < 2 times current system cost | Advanced Technology Low-Cost Engine | RL-10C P&W |
| | 50 ± klb s.l. thrust | 400 klb thrust | 35 klb thrust |
| | I(sp) 450 (vac) | vac<br>D57 (Russia) 90 klb thrust<br>450 sec I [sp(Vac)] | 463 sec I[sp(vac)]<br>D57 (Russia) 90 klb thrust<br>450 secI[sp(vac)] |
| | I(sp) 380 (vac) | 410 sec I[sp(vac)]<br>0.307 sec I(sp)(s.l.)<br>STE(NLS) 650 klb thrust<br>428.5 sec I[sp(vac)]<br>STE 130 640 klb thrust<br>456 sec I[sp(vac)] | TRW Pintle Engine 733 klb thrust<br>393 sec I[sp(vac)] |
| - $LO_2/LH_2$ Booster | < 2 times current system cost<br>550 klb s.l. thrust<br>380 sec I[sp(vac)] | Approximately $60 million<br>350 klb s.l. thrust<br>450 sec I[sp(vac)] | Approximately $60 million<br>350 klb s.l. thrust<br>450 sec I[sp(vac)] |
| - $LO_2$/RP-1 Booster | < 2 times current system cost<br>300 klb s.l. thrust<br>275 sec I[sp(vac)] | RD 170 (Russia)<br>1.8 Mlb thrust<br>337 sec I[sp(vac)] | MA-5B<br>337 klb thrust<br>334 sec I[sp(vac)] |
| - Hybrids | Price equal to monolithic solids<br>> 400 klb thrust<br>275 sec I[sp(vac)] | 25–40 klb thrust (s.l.)<br>< 270 sec I[sp(vac)] | 25–40 klb thrust (s.l.)<br>< 270 sec I[sp(vac)] |

* Typical of nuclear engine for rocket vehicle application (NERVA) Technology

**Table III-17. Technology Capabilities: Power and Thermal Management**

| Technology | Military Parameters | Current Laboratory Capabilities | Current Industry Production Capabilities |
|---|---|---|---|
| Solar—Photovoltaic | Production technology: Specific power > 300 W/m$^2$ BOL at 28 °C at cell level | Production technology: Specific power > 325 W/m$^2$ BOL at 28 °C at cell level | Production technology: Specific power > 240 W/m$^2$ BOL at 28 °C at cell level |
| Solar—Dynamic | Production technology: System-specific power > 25 W/kg | Production technology: System-specific power @ 15 W/kg | Production technology: None |
| --Materials | All refractory heat engine components at temperatures > 1250 K | All refractory heat engine components at temperatures > 1250 K | All refractory heat engine components at temperatures > 1250 K |
| --Software | Capable of analysis of all transient heat engine cycle performance | Capable of analysis of all transient heat engine cycle performance | Capable of analysis of all transient heat engine cycle performance |
| Nuclear Radioisotope --Materials | Plutonium 238 > 1 gram Neptunium 237 > 1 gram | Plutonium 238 > 1 gram Neptunium 237 > 1 gram | Plutonium 238 > 1 gram Neptunium 237 > 1 gram |
| Nuclear Fission --Materials | High-purity refractory metals at > 1250 K High-temp thermoelectric materials > 1000 K Highly enriched uranium > 20 percent U-235 | High-purity refractory metals at > 1250 K High-temp thermoelectric materials > 1000 K Highly enriched uranium > 20 percent U-235 | High-purity refractory metals at > 1250 K High-temp thermoelectric materials > 1000 K Highly enriched uranium > 20 percent U-235 |
| --Components | Radiation-resistant electrical insulators > 1.0 E+18 nvt* | Radiation-resistant electrical insulators > 1.0 E+18 nvt | Radiation-resistant electrical insulators > 1.0 E+18 nvt |

* nvt = neutron velocity time

## Table III-17. Technology Capabilities: Power and Thermal Management (Continued)

| Technology | Military Parameters | Current Laboratory Capabilities | Current Industry Production Capabilities |
|---|---|---|---|
| Long-life Cryogenic Coolers | Temp: / Efficiency (W/W)* | | |
| | (1) 120–180 K < 10 | (1) 1W @ 150 K 12 W/W, < 1 N rms life TBD | (1) None |
| | (2) 60–80 K < 75 | (2) 2W @ 60 K 50 W/W, < 1 N rms life TBD | (2) 800 mW @ 80 K 75 W/W, > 1 N rms |
| | (3) 30–40 K < 200 | (3) 1 W @ 35 K 200 W/W, < 1 N rms | (3) None |
| | (4) 9–11 K < 750 | (4) No lab results | (4) None |
| | Vibration: < 0.02 N rms | | |
| | Unattended life: 7 years | | |
| | Cooling loads:<br>(1) 120–180 K < 10 W<br>(2) 60–80 K < 5 W<br>(3) 30–40 K < 1 W<br>(4) 9–11 K < 0.5 W | | |
| Spacecraft Thermal Control | | | |
| --Liquid Metal Heat-Pipes | > 600 K | > 600 K | > 600 K |
| --Advanced Radiators (Composite) | < 30 kg/kW<br>< 7 $m^2$/kW | < 30 kg/kW<br>< 7 $m^2$/kW | < 30 kg/kW<br>< 7 $m^2$/kW |
| --High-Power Density Electronics Cooling | > 1000 W/$cm^2$ | < 500 W/$cm^2$ | < 100 W/$cm^2$ |
| Energy Storage--Batteries | Components with an energy density of:<br>100 W-hr/kg > 1000 cycles<br>75 W-hr/kg > 25,000 cycles<br>> 250 W-hr/kg (primary battery) | Components with an energy density of:<br>60 W-hr/kg > 1000 cycles<br>40 W-hr/kg > 25,000 cycles<br>> 200 W-hr/kg (primary battery) | Components with an energy density of:<br>60 W-hr/kg > 1000 cycles<br>40 W-hr/kg > 25,000 cycles<br>> 150 W-hr/kg (primary battery) |

* Watts input power per watt of cooling

**Table III-18. Technology Capabilities: Communications**

| Technology | Military Parameters | Current Laboratory Capabilities | Current Industry Production Capabilities |
|---|---|---|---|
| Antennas | | | |
| --Adaptive | Null depth > 25 db, adaptation time < 10 msec | Same as militarily critical | Same as militarily critical |
| --Integrated Phased Array | Number of radiating elements > 1000 | | |
| --Multi-Beam Antennas | Spatial resolution single beam < 0.5 degrees | | |
| --Side Lobe Control | | | |
| - Reflectors | Side lobe > 35 db at aspect angles > 5 degrees | Same as militarily critical | Same as militarily critical |
| - Phased Arrays | Side lobe > 50 db below the mean peak | | |
| Space Solid-State Amplifiers | 250 MHz > 25 W<br>8 GHz > 2 W<br>20 GHz > 3 W<br>60 GHz > 1/4 W<br>10 yr, 30 percent efficiency | Same as militarily critical | Same as militarily critical |
| Receiver | | | |
| --High Data Rate | > 1 Gb per second | Same as militarily critical | Same as militarily critical |
| --Spread Spectrum | | | |

Table III-19. Technology Capabilities: Electronics and Computers

| Technology | Military Parameters | Current Laboratory Capabilities | Current Industry Production Capabilities |
|---|---|---|---|
| Architecture | | | |
| --Digital Signal Processors | Rad hard > 1 Mrad<br>Throughput > 1 MOPs<br>Reprogrammable | Rad hard < 1 krad<br>Throughput > 1 GFLOPs<br>Hard-wired | Rad hard > 1 Mrad<br>Not programmable<br>Hard-wired |
| --High Speed Data Buses | Rad hard > 1 Mrad<br>Throughput > 1 MOPs | Rad hard < 1 krad<br>Throughput > 1 GFLOPs | Rad hard > 1 Mrad<br>Not programmable |
| Rad Hard Electronics Technology | | | |
| --Archival Data Storage Systems | Rad hard > 1 Mrad<br>Capacity > 10 GB<br>Continuous operation > 10 years | Rad hard > 250 krad<br>Capacity = 1 GB<br>Continuous operation > 5 years | Tape drives (not random access)<br>> 1 Mrad |
| --Electronics/Computers | Rad hard > 1 Mrad<br>Low-cost product line | Rad hard > 1 Mrad | Rad hard > 1 Mrad |
| --Cryogenic Electronics | Rad hard > 500 krad | Rad hard > 100 krad | No rad hard capability |
| --Field Programmable Devices | Rad hard > 500 krad<br>Density > 5 k gates | No rad hard capability | No rad hard capability |
| --Nonvolatile Memory | Rad hard > 1 Mrad<br>Retention > 10 years<br>Endurance > 1.0 E+12 cycles | Rad hard > 1 Mrad<br>Retention > 5 years<br>Endurance > 1.0 E+10 cycles | Rad hard > 1 Mrad<br>Retention > 5 years<br>Endurance > 1.0 E+5 cycles |
| --Packaging | Rad hard > 10 Mrad<br>Hermetic seal<br>Density improvement > 10 X | Rad hard > 10 Mrad<br>Hermetic seal<br>Density improvement > 10 X | Rad hard > 10 Mrad<br>Hermetic seal<br>Density improvement > 3 X |
| --Neural Networks | Rad hard > 1 Mrad<br>2–3000 connections | None | None |
| --Dielectrically Isolated Materials (SOI) | Film thickness < 0.3 µm<br>Uniformity > 95 percent<br>Defects < 10/cm$^2$ | Film thickness < 0.3 µm<br>Uniformity > 99 percent<br>Defects < 1.0 E+3/cm$^2$ | Film thickness < 0.3 µm<br>Uniformity > 96 percent<br>Defects < 1.0 E+5/cm$^2$ |

**Table III-19. Technology Capabilities: Electronics and Computers (Continued)**

| Technology | Military Parameters | Current Laboratory Capabilities | Current Industry Production Capabilities |
|---|---|---|---|
| Computer Technology | | | |
| --Software | Fault-tolerant<br>On-orbit reprogrammability | Fault-tolerant<br>Ground reprogrammability | Fault-tolerant<br>Ground reprogrammability |
| --Optical Domain Data Processing | Rad hard > 500 krad | Rad hard > 100 krad | None produced |
| --Opto-Electronic Integrated Circuits | Rad hard > 500 krad | Rad hard > 100 krad | None produced |

## Table III-20. Technology Capabilities: Astronautics

| Technology | Military Parameters | Current Laboratory Capabilities | Current Industry Production Capabilities |
|---|---|---|---|
| Ring Laser | Bias < 0.003 degree drift rate/hr<br>Random walk 0.0015 degree/√hr<br>Scale factor < 5 ppm<br>Colored noise < 0.003 degree/hr<br>Misalignment 1.5 arc sec | Bias < 0.01 degree drift rate/hr<br>Random walk 0.08 degree/√hr<br>Scale factor < 100 ppm<br>Colored noise < 0.035 degree/hr<br>Misalignment 20arc sec | Bias < 0.003 degree drift rate/hr<br>Random walk 0.0015 degree/√hr<br>Scale factor < 5 ppm<br>Colored noise < 0.003 degree/hr<br>Misalignment 1.5 arc sec |
| Fiber Optic Gyro | Bias < 0.1 degree drift rate/hr<br>Random walk 0.08 degree/√hr<br>Scale factor < 100 ppm<br>Colored noise < 0.035 degree/hr<br>Misalignment 20 arc sec | Bias < 0.1 degree drift rate/hr<br>Random walk 0.08 degree/√hr<br>Scale factor < 100 ppm<br>Colored noise < 0.035 degree/hr<br>Misalignment 20 arc sec | Bias < 0.1 degree drift rate/hr<br>Random walk 0.08 degree/√hr<br>Scale factor < 100 ppm<br>Colored noise < 0.035 degree/hr<br>Misalignment 20 arc sec |
| Accelerometers | Bias < 25 μg<br>White noise < 10 μg/√hz<br>Scale factor < 120 ppm<br>Colored noise < 15 μg<br>Misalignment 0.2 arc sec | Bias < 5 μg<br>White noise < 2 μg/√hz<br>Scale factor < 25 ppm<br>Colored noise < 3 μg<br>Misalignment 0.5 arc sec | Bias < 25 μg<br>White noise < 10 μg/√hz<br>Scale factor < 120 ppm<br>Colored noise < 15 μg<br>Misalignment 0.2 arc sec |
| GPS-Aided Navigation | Subsystem rel > 0.9999<br>Vib > 50 gs<br>SEU resilient<br>Latch-up free<br>Position error:<br>X = 0.3, Y = 0.3,<br>Z = 0.3 m at 3 gs for 3 axis | Demonstrated to position error of<br>X = 0.3, Y = 0.3, Z = 0.3 m<br>at 3 gs for 3 axis | Position error better than<br>X = 0.3, Y = 0.3, Z = 0.3 m<br>at 3 gs for 3 axis |

Table III-21. Technology Capabilities: Optics

| Technology | Military Parameters | Current Laboratory Capabilities | Current Industry Production Capabilities |
|---|---|---|---|
| Directed Energy Optics | < 1.0 E-3 absorption<br>> 1.0 E+4 W/cm$^2$ incident radiation | < 200 ppm (2.0 E-4) absorptance at 2.7 μm<br>Incident radiation power density achievable is beyond that of military parameters and is classified | < 200 ppm (2.0 E-4) absorptance — Alpha Laser /Large Aperture Mirror Program (ALI/LAMP) at 2.7 μm |
| Lightweight Space Qualified Optics | < 20 percent bulk weight<br>30 kg/m$^2$ areal density<br>Total weight > 10 kg<br>> 1 m aperture | < 20 percent bulk weight | Hubble 2.3 m aperture<br>Approx. 30 percent bulk weight |
| Passively and Actively Cooled Optics | > 1.0 E+4 W/cm$^2$<br>Incident radiation for 30 sec | > 1.0 E+4 W/cm$^2$<br>Incident radiation for 30 sec | > 1.0 E+4 W/cm$^2$<br>Incident radiation for 30 sec |
| Adaptive Optics | > 10 cm aperture<br>> 100 Hz bandwidth<br>< 1/2 λ flatness for > 100 Hz band-width<br>λ = 0.5 μm | > 20 cm aperture achievable<br>> 500 Hz bandwidth achievable<br>< 1/2 λ flatness for > 100 Hz band width<br>λ = 0.5 μm | > 20 cm aperture achievable<br>> 500 Hz bandwidth achievable<br>< 1/2 λ flatness for > 100 Hz band width<br>λ = 0.5 μm |
| Silicon Optics | Single crystal substrate w/optical coating<br>< 200 ppm absorption total (substrate and coating)<br>> 25 cm aperture<br>< 200 ppm optical scatter | (Absorption measurement not complete but typically > 200 ppm)<br>> 45 cm aperture | Absorption not measured (only on witness samples)<br>> 45 cm aperture |
| Optical Coatings | Scatter < 3.0 E-3 and absorption < 1.0 E-3 (for surface > 30-cm diameter) | Si optics < 100 ppm scatter and < 100 ppm absorptance at 2.7 μm (dependent upon wavelength, substrate, and size of optic) | Si optics < 100 ppm scatter and < 100 ppm absorptance at 2.7 μm (dependent upon wavelength, substrate, and size of optic) |
| Segmented Optics | > 1 m aperture equivalent | Large Aperture Mirror Program (LAMP)<br>4 m aperture | Large Aperture Mirror Program (LAMP)<br>4 m aperture |

**Table III-22. Technology Capabilities: Vulnerability and Survivability**

| Technology | Military Parameters | Current Laboratory Capabilities | Current Industry Production Capabilities |
|---|---|---|---|
| Nuclear/Natural Radiation Hardening | Total dose > 5.0 E+5 rads(Si)<br>Dose rate > 5.0 E+8 rads(Si)/sec<br>SEU < 1.0 E–7 errors/bit/day<br>Newton fluence > 1.0 E+10 n/cm$^2$ | Total dose > 1.0 E+8 rads(Si)<br>Dose rate > 1.0 E+10 rads(Si)/sec<br>SEU < 1.0 E–9 errors/bit/day<br>Newton fluence > 1.0 E+13 n/cm$^2$ | Total dose > 1.0 E+6 rads(Si)<br>Dose rate > 1.0 E+9 rads(Si)/sec<br>SEU < 1.0 E–8 errors/bit/day<br>Newton fluence > 1.0 E+12 n/cm$^2$ |
| Electromagnetic Pulse | Field strength > 30 kV/m | Field strength > 60 kV/m | Field strength > 50 kV/m |
| High-Power RF Filters for Sensor Optics | > 40 db attenuation of RF energy and > 96 percent transmission of sensor frequency | > 40 db attenuation of RF energy and > 96 percent transmission of sensor frequency | > 40 db attenuation of RF energy and > 96 percent transmission of sensor frequency |
| Signature Identification for Space Objects | Codes and algorithms with range of frequency from vacuum UV (0.11 µ) through LWIR (25 µ) | Codes and algorithms with range of frequency from vacuum UV (0.11 µ) through LWIR (25 µ) | None |
| Laser Effects | Energy density > 1.0 E–3 joule/cm$^2$ with dwell times > 1 µsec | Energy density > 1.0 E–3 joule/cm$^2$ with dwell times > 1 µsec | Energy density > 1.0 E–3 joule/cm$^2$ with dwell times > 1 µsec |

Table III-23. Technology Capabilities: Qualification and Testing

| Technology | Military Parameters | Current Laboratory Capabilities | Current Industry Production Capabilities |
|---|---|---|---|
| Thermal Vacuum Simulation | 1.0 E–8 Torr<br>– 320 to + 250 °C | Parameters are achievable in volumes up to 250 $ft^3$ (down to –150 °C) | Parameters are achievable in volumes up to 1000 $ft^3$ (down to –150 °C and 1.0 E–7 Torr) |
| Space Environmental Simulation | 1.0 E-5 Torr | Parameters currently achievable one to four at a time only (not all six parameters simultaneously) | Parameters currently achievable one to four at a time only (not all six parameters simultaneously) |
| --Atomic Oxygen | Energy 5 eV<br>Flux 1.0 E+14/$cm^2$ | | |
| --Electrons | Energy 500 eV<br>Flux 1.0 E+12/$cm^2$/MeV | | |
| --Protons | Energy 1 MeV<br>Flux 1.0 E+7/$cm^2$/MeV | | |
| --UV Radiation | 100 nm to 400 nm (1 sun equivalent) | | |
| --Temperature | –130 to 100 °C | | |
| --Hypervelocity Debris | Size 0.1 mm–1.0 mm<br>Flux 1.0 E–2 to 1.0 E+21 nits/hr/$m^2$<br>Velocity ~ 10 km/sec | | |

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# GLOSSARY

| | |
|---|---|
| 1D | one dimensional |
| 2D | two dimensional |
| 3D | three dimensional |
| AI | artificial intelligence |
| Al-Li | aluminum-lithium |
| BIST | built-in self test |
| BIT | built-in test |
| BOL | beginning of life |
| C-C | carbon-carbon |
| CAD | computer-aided design |
| CAM | computer-aided manufacturing |
| cc | cubic centimeter |
| CCD | charged coupled device |
| CRDA | Cooperative Research and Development Agreement |
| CFD | Computational Fluid Dynamics |
| db | decibel |
| DoD | Department of Defense |
| DSB | Defense Science Board |
| DSP | Deep Space Probe |
| EMC | electromagnetic capability |
| EMP | electromagnetic pulse |
| EPS | Environmental Protection System |
| FPA | focal plane array |
| GaAS | gallium arsenide |
| Gb | gigabit |
| GB | gigabyte |
| GHz | gigahertz |
| GLONASS | Global Navigation Satellite System |
| gm | gram |
| GPS | Global Positioning System |

| | |
|---|---|
| HDTV | high-definition television |
| HEL | high-energy laser |
| Hz | hertz |
| ICBM | intercontinental ballistic missile |
| IR | infrared |
| kg | kilogram |
| kN | kilo-newton |
| kW | kilowatt |
| ladar | laser detecting and ranging |
| LAMP | Large Aperture Mirror Program |
| LANDSAT | land satellite |
| LDEF | Long-Duration Exposure Facility |
| LWIR | long wave infrared |
| MCTL | Militarily Critical Technologies List |
| MEMS | Micro-Electronic-Mechanical System |
| MGB | multi-band gap |
| MHz | megahertz |
| MILSATCOM | military satellite communications |
| mm | millimeter |
| MN | mega-newton |
| MOU | Memorandum of Understanding |
| MPa | megapascals |
| N | newton |
| NaS | sodium-sulfur |
| NASA | National Aeronautics and Space Administration |
| NERVA | nuclear engine for rocket vehicle application |
| NiCd | nickel-cadium |
| $NiH_2$ or $NiMH_2$ | nickel-hydrogen |
| nvt | neutron velocity time |
| ppm | parts per million |
| PV/W | pressure-volume/weight |
| R&D | research and development |
| radar | radio detecting and ranging |
| RDT&E | research, development, test, and evaluation |

| | |
|---|---|
| RF | radio frequency |
| rms | root mean square |
| S/N | signal-to-noise |
| SE&I | Systems Engineering and Integration |
| sec | second |
| SEMP | single expansion mode pulse |
| Si | silicon |
| SSP | solid-state polymer |
| SSTWG | Space Systems Technology Working Group |
| TBD | to be determined |
| TIAC | Technology and Identification Analyses Center |
| UV | ultraviolet |
| W | watt |
| W/W | watts input power per watt of cooling |

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The speed with which a promising military critical technology becomes available for military use is determined to a great extent by the effort and support focused on that technology. Determining which space technologies deserve this attention requires knowing at what performance level or technical parameter the technology becomes militarily critical. The Space System Technology Working Group (SSTWG) identified and parametrized those space technologies that are militarily critical, space unique, and dual-use and those that should be considered for cooperative agreements with industry and academia and memorandum of understanding (MOU) with other countries. This Executive Report provides government, industry, and academic personnel concerned with space technologies the purpose, methodology, and results of the SSTWG study. It includes tables that identify critical space technologies and their parameters.

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